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QUANTITATIVE RESPIRATOR FIT TESTING THROUGH DYNAMIC PRESSURE MEASUREMENT

A thesis submitted to the

Division of Graduate Studies
of the University of Cincinnati

in partial fulfillment of the
requirements for the degree of

MASTER OF SCIENCE

in the Department of Environmental Health
of the College of Medicine

1987

by

David R. Carpenter

B.S. The Pennsylvania State University, 1979

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I hereby recommend that the thesis prepared under my supervision by David R. Carpenter

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be accepted as fulfilling this part of the requirements for the degree of Master of Science

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ABSTRACT

Respirators are worn throughout industry and the Armed Forces to provide workers protection. To ensure respirators fit adequately, quantitative fit testing is performed. Unfortunately, current methods of quantitative fit testing have serious limitations. These limitations include dependency of the measured leakage on leak location and the cost of equipment. These limitations have led to a search for a new method for quantitative fit testing.

The purpose of this study was to evaluate a new method of quantitative fit testing, "Quantitative Respirator Fit Testing Through Dynamic Pressure Measurements", patent applied for by the University of Cincinnati, Klaus Willeke author. The evaluation of this method was limited to determining if leak location and sensor location effected the measured pressure decay in a sealed respirator. Also, a comparison of the pressure decay method was made to an aerosol fit test method to determine if a relationship existed between the two methods.

To perform the evaluation of the pressure decay method, modifications to three respirators were made. Each respirators was probed in three locations on the periphery. These probes were used to produce artificial leak locations. Leak holes of different diameters were attached to the probes. A filter coupling was constructed which allowed the

placement of test equipment onto the respirator without removal of the respirator from the subject's face. To measure only the artificial leak introduced, the respirator was sealed to the subject's face. Once the respirator was secured, the appropriate equipment was attached to the respirator to perform the pressure or aerosol test.

The results of this study indicated the dynamic pressure decay method of quantitative fit testing is independent of leak and sensor location. The relative error of the pressure decay method was less than the relative error of the aerosol method. A full cost analysis was not performed to determine if the dynamic pressure method is less expensive than the aerosol method. However, the cost of the equipment for the pressure measurement system was less than three thousand dollars. This included the pressure transducer, computer hardware, computer and computer software. In practice, less sophisticated equipment would be required for field level testing. This would reduce the cost to less than two thousand dollars. This cost compared to the eight to seventeen thousand dollars for aerosol test equipment makes the pressure decay method economically attractive. Further studies are required however, the results of this study indicates dynamic pressure measurement is a superior method compared to the aerosol method for quantitative fit testing of respirators.

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The completion of this thesis within my time constraints would not have been possible without the efforts of many. First, I would like to express my gratitude to my thesis committee. Mr. Carl Miller spent a great deal of time with me initially. From his efforts, I gained a great deal of knowledge and practical experience in quantitative fit testing in the field. Professor Howard Ayer has always been available for discussion. His ability to listen, then advise aided tremendously in working through many problems. I would like to thank Dr. Klaus Willeke, my advisor, for the opportunities the past 14 months have given to me. Our numerous discussions, time in the laboratory, and his open door has truly made this thesis a learning experience. I would also like to express my appreciation to Ann Sherman, my lab partner and Carol Stevens, a very good friend.

I would not have accomplished my thesis without the unyielding support of my wife, Janice. Her support and assistance throughout and especially these last few days has been unmeasurable.

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NOMENCLATURE

B	-	Bottom
CL	-	Center Left
conc	-	Concentration
CR	-	Center Right
dia	-	Diameter
Σ	-	Eta
I.D.	-	Internal Diameter
K	-	Willeke Leak Slope
ln	-	Natural Logarithm
MSD	-	Metropolitian Sewer District
N	-	Number Count
NIOSH	-	National Institute for Occupational Safety and Health
OSHA	-	Occupational Safety and Health Administration
P	-	Pressure
PVC	-	Polyvinyl Chloride
R	-	Range
T	-	Top
t	-	Time (seconds)
V	-	Volume

WFF - Willeke Fit Factor

WLS - Willeke Leak Slope

w.g. - Water Gage

WPN - Willeke Protection Number

WRV - Willeke Respirator Volume

Y - Percent Full Scale Deflection

QUANTITATIVE RESPIRATOR FIT TEST THROUGH DYNAMIC PRESSURE MEASUREMENT

Chapter One

Introduction

Respirators are worn in industry and Armed Forces to reduce the inhalation of contaminants. These contaminants include vapors, gases and aerosols. The best protection, generally, is provided by a full-face piece respirator. Frequently, however a negative pressure half-face respirator is chosen as the respirator of choice for lower costs, less burden on the user and less visual obstruction. This type of respirator covers the face from the bridge of the nose to underneath the chin. When the user inspires, a negative pressure is produced in the respirator cavity pulling air through the filters.

Any contamination entering the respirator cavity, resulting in the user's exposure to this contaminant, is due to failure of either the filter or the face seal. In the half-face, negative pressure respirator, with replaceable filters, the incomplete face seal is generally the major cause of leakage. To determine the amount of leakage into the respirator cavity, several test methods have been developed. These methods can be categorized into two types,

qualitative and quantitative fit test methods. In both methods currently in use, the integrity of the face seal is determined by the perception or detection of a test atmosphere inside the respirator cavity relative to its concentration outside the respirator cavity.

This thesis examines a new method of quantitative fit testing and compares, on a limited basis, the new method to a quantitative fit test method using a corn oil aerosol. In this new method, "Quantitative Respirator Fit Testing through Dynamic Pressure Measurements", the respirator fit is determined through dynamic pressure measurement. A patent for this method, developed by Klaus Willeke, has been applied for by the University of Cincinnati. Figure 1.1 demonstrates the principle on a subject wearing a respirator with modified filter cartridges. The subject holds his or her breath, the respirator cavity is sealed, and a negative pressure is applied. In the following seconds, the pressure decay is measured. The results are then viewed on a electronic read-out device.

The goals of this thesis are to determine experimentally, the effects of leak location, sensor location and respirator cavity volume on the measured pressure decay. The same parameters will be studied to determine the effects on the measured aerosol leakage.

A comparison of the pressure decay and aerosol leakage will be made to determine which method is more sensitive and precise.

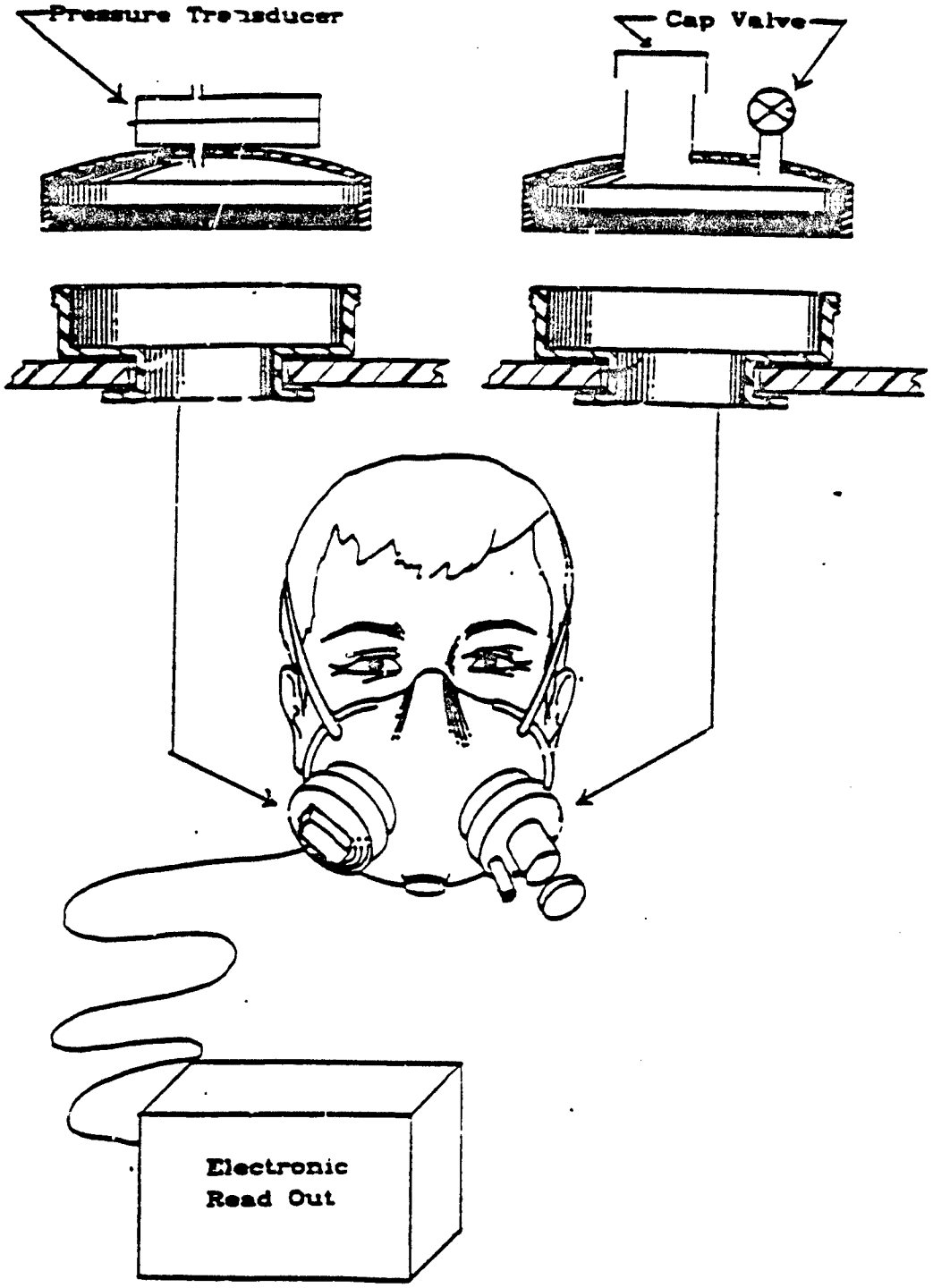

Figure 1.1 The Negative Pressure Decay Method.

Chapter Two

Background

Respirators are worn in private industry and the Armed Forces to reduce inhalation of airborne contaminants (US Congress, Office of Technology, 1982). A poor fitting respirator will allow penetration of contaminants from the work place environment into the respirator. To insure workers are adequately protected by the use of respirators, fit testing is performed. There are two general types of respirator fit tests: qualitative fit tests and quantitative fit tests. In qualitative fit testing, the leakage into the respirator is assessed by the user's ability to detect a taste, odor or pressure. In quantitative fit testing, the concentration of a test environment inside the respirator is compared to its concentration outside the respirator by use of a detector.

2.1 Qualitative Fit Testing

The most common qualitative fit tests (Hardis et al, 1983) are isoamyl acetate, irritant smoke or sodium saccharin. Another common qualitative method is the pressure test.

2.1.1 Isoamyl Acetate Test

Isoamyl acetate, a liquid at standard temperature and pressure, has a strong odor simular to that released by ripe bananas (Schabe, 1980). The subject is challenged with isoamyl acetate, without respiratory protection, to ensure the subject can perceive the odor. Next, the subject wearing respiratory protection, enters a chamber with the isoamyl acetate vapor challenge environment. After two minutes of steady breathing without head movements, if the subject does not perceive the isoamyl acetate, head and facial movements are carried out. The subject passes the test if no isoamyl acetate is perceived at any time.

2.1.2 Irritant Smoke Test

Stannic oxychloride or titanium tetrachloride is exposed to moisture from the air to produce a fume containing hydrogen chloride absorbed on small solid particles (Marsh, 1984a). Starting at 30 cm from the subject's face, the smoke is directed toward the face/respirator interface. The smoke tube is moved to within 2 to 3 cm of the subject's face. If during any time the subject begins to cough or sneeze, the test is terminated and considered a failure.

2.1.3 Sodium Saccharin Test

In the sodium saccharin test (Marsh, 1984b),as with the isoamyl acetate test, the subject is first tested without respiratory protection to insure he or she can perceive the sodium saccharin. A portable hood, covering the head and neck area, is placed over the subject wearing a respirator. A sodium saccharin solution, ten times stronger than the perception test solution, is atomized into the hood. If the subject detects the sodium saccharin while wearing the hood, the fit is considered inadequate.

2.1.4 Pressure Test

In the pressure test, the subject dons the respirator, covers the inlets and inhales. The subject determines, by sensation, if a negative pressure is produced and if the negative pressure is maintained. Then the subject covers the exhalation valve and exhales. This time the subject determines if a positive pressure is created in the respirator cavity and determines if the positive pressure is maintained.

2.2 Quantitative Fit Testing

2.2.1 Quantitative Fit Test Methods

Quantitative fit testing can be performed with numerous substances. Table 2-1 (Holton, 1986) lists many of the test

agents and associated detection instruments. The most used agents are sodium chloride and corn oil. During the testing, the subject performs head movements, speaking, deep breatning and exercising to determine the reliability of the face seal. In quantitative fit testing a fit factor is assigned after testing. The fit factor is the concentration of the test agent in the test chamber divided by the average concentration in the respirator cavity.

2.2.2 Sodium Chloride Method

A polydisperse sodium chloride test aerosol is generated by nebulization of an aqueous sodium chloride solution (Douglas, 1977). The aerosol is dried by dilution air and injected into the top of the test chamber. Samples of sodium chloride are taken from the chamber and the respirator cavity. The concentration of the sodium chloride is determined by hydrogen flame photometery. With the measured concentration in the respirator cavity and of the test chamber, a fit factor is determined.

2.2.3 Corn Oil Method

Corn oil is nebulized to produce a polydisperse aerosol and is injected into the top of a test chamber (Hyatt et al, 1972 and U.S. Department of Health and Human Services, 1983) Samples are taken from the chamber and the respirator cavity.

Table 2.1
Quantitative Fit Test Agents (adapted from Holton, 1986)

Test Agent	Detection Instrument	Reference
Amyl Acetate	Gas Liquid Chromatography	Schabe, 1980
Argon	Mass Spectrometer	Griffin, 1970
Ethylene	Detector Tubes	Pasternack, 1978
Freon 12	Davis Halide Meter	Adley, 1962
Helium	Mass Spectrometer	Cyr, 1975
Methane	Gas Liquid Chromatography	Schwabe, 1980
Penthrane	Gas liquid Chromatography	Schwabe, 1980
Sulfur Hexaflouride	Flame Photometer	Douglas, 1977
Bacillus Substilis	Bacteriological Plating	Guyton, 1967
Carbon Particles	Condensation Nucleus Counter	Willeke, 1981
Corn Oil	Light scattering Photometer	Hinds, 1983
Di-2-ethyhexyl Phthlate	Light Scattering Photometer	Hyatt, 1972
Sodium Chloride	Flame Photometer	Douglas, 1977
Uranine	Fluorometer	Burgess, 1961

The samples are analyzed by a light scattering photometer. From these samples, a fit factor is determined.

2.3 Disadvantages of Qualitative and Quantitative Fit Tests

Both qualitative and quantitative fit testing have disadvantages. For qualitative fit tests of half face respirators, a successful test is equivalent to a fit factor of ten (U.S. Department of Labor, 1982). Also, in qualitative fit testing the ability of the subject to detect and report correctly the appropriate sensation is assumed accurate and is not validated. In quantitative fit testing, it has been shown that probe location and hole location effect the measured concentration in the respirator cavity (Myers, 1986). In field studies of effective protection factors, the results are generally not corrected for the effects of lung deposition of the aerosol to which the worker is exposed. These factors lead to underestimation of the penetration of the test environment and overestimation of the fit factor. Based on these disadvantages in current respirator fit testing, alternative methods have been sought for possible use.

2.4 Recent Developments

Two methods have been studied for respirator fit testing by the use of pressure measurement. These methods are slack tube manometer method and the dynamic pressure decay method, the latter being the subject of this thesis.

2.4.1 Slack Tube Manometer Method

A method used by the Louisville and Jefferson County Metropolitan Sewer District (MSD) provided a quick, inexpensive method for testing respirator fits prior to entering contaminated areas. The MSD did not wish to rely on existing qualitative fit test methods for their employees. Under the guidance of consultants, a method was developed to check respirator fits. A slack tube manometer was connected to the respirator by a piece of tygon tubing. The user produced a negative pressure inside the respirator by taking a breath. The fit was considered adequate if the pressure was maintained for a specified period of time. Comparative studies of the slack tube method to predetermined fit factors, as measured by the corn oil method, were accomplished at the University of Cincinnati (Foltz, 1985) under the direction of Carl Miller. Using predetermined pressure and time criteria, the study indicated the slack tube manometer method was superior to the qualitative fit test method. In these studies, pass-fail criteria were used

in comparing the fit factor to the overall pressure decay for a 10 second period. The issue of leak location, tube length, tube diameter, response time of a slack tube manometer, and overall test system response time were not evaluated or controlled for.

2.4.2 Dynamic Pressure Decay Method

In quantitative fit testing with aerosols, the leak hole and probe location effect the measured aerosol penetration (Myers, 1986). This is impart due to the lack of time for complete mixing of the aerosol in the respirator cavity. In the pressure decay method, the pressure decay is independent of leak and sensor location (Willeke 1985). In the dynamic pressure decay method, the pressure sensor is located directly on the respirator cavity. The sensor has a response time of less than ten milliseconds with an electronic read-out device capable of receiving the data. This should allow the results to be repeatable from one system to the next.

Chapter Three

Calculations

In this study data are collected using an aerosol method and a pressure decay method to determine leakage into a respirator. After the data is collected, the data must be transformed by a logical sequence into usable information. The leak hole diameters and leak locations are controlled by the experimenter. Since the leak hole diameters are predetermined, an attempt has been made to quantify the leak holes not only by the diameters but also by the volumetric flow rates for given pressure differentials across the leak holes.

3.1 Aerosol Calculations

In the aerosol method a near forward light scattering photometer has been used to measure the aerosol concentration. The measured concentration will be then saved by a strip recorder. To determine the leakage of aerosol into the respirator cavity, interpretation of the strip chart is required.

The photometer is equipped with a multiplier to enhance signal resolution. This multiplying capability is referred to as the range. Each time the photometer reading is less

than ten percent full scale response the signal can be amplified by a factor of 10. The ranges,R, available on the photometer used were 100, 10, 1 and 0.1 percent. The corresponding multiplying factors are 1, 10, 100 and 1000.

The concentration of the test chamber was arbitrarily set at 100 percent full scale response on the 100 percent range. The concentration inside the respirator cavity was a fraction of this amount. To determine this fraction for each data point, the following equation was used:

$$\text{conc} = \%\ \text{full scale response} \times \text{range} \qquad (3.1)$$

To determine the fit factor, the test chamber concentration was divided by the average concentration in the respirator cavity:

$$\text{Fit Factor} = \frac{100}{(\sum(Y \times R)/N)} \qquad (3.2)$$

where N is the total number of data points for the test, Y is the percent full scale deflection and R is the range value.

It was found convenient for discussion to refer to the aerosol leakage in terms of percent aerosol leakage. This was calculated by the following equation:

$$\text{Aerosol leakage, \%} = \frac{1/N\sum(Y \times R)}{100} \times 100 \qquad (3.3)$$

or

$$\text{Aerosol leakage, \%} = \frac{100}{\text{Fit Factor}} \qquad (3.4)$$

3.2 Pressure Decay Calculations

The calculations for the pressure decay data were defined by the patent application (Willeke 1985). They are:

WLS = Willeke Leak Slope

$$= \frac{\ln P_1 - \ln P_2}{t_2 - t_1} = \frac{\ln(P_1/P_2)}{t_2 - t_1} \qquad (3.5)$$

where P is the pressure measured in cm w.g. and t is the time in seconds.

WFF = Willeke Fit Factor (3.6)

$$= 1/(WLS \times t)$$

where t is a specified period of time

WRV = Willeke Respirator Volume

= the volume of the respirator cavity as determined by the leak hole test

WLR = Willeke Leak Rate

$$= WLS \times WRV \qquad (3.7)$$

The flow through the leak hole is defined as:

$$Q_{leak} = K \times WLR \qquad (3.8)$$

where K is a constant to be determined experimentally

WPN = Willeke Protection Number

$$= \frac{Q_{inhalation}}{Q_{leak}} \qquad (3.9)$$

3.3 Pressure Response to Volumetric Flow through the Leak Hole

In determining equations 3.6, 3.7, 3.8 and 3.9 there is an assumption the volumetric flow rate and pressure decline across the leak holes are related. This relationship is expressed by the equation (Kreith 1957):

$$P = AQ^b \qquad (3\text{-}10)$$

where A and b are assumed constants. The factor b is related to the flow pattern and changes as the flow pattern goes from laminar to turbulent flow. The flow pattern through the leak holes at low pressure are not known and could not be found in the literature. To evaluate equations 3.6 through 3.9, the b term in equation 3.10 must be proven constant in the pressure range of this experiment. In this study, the primary concern was determining the aerosol leakage and leak slope for given leak locations and leak holes. A preliminary experiment has been performed to determine the b factor of equation 3.10. If factor b is constant, equations 3.6 through 3.9 can evaluated. If b is not constant, the relationships then becomes complex and the equations 3.6 through 3.9 can not be evaluated as shown.

Chapter Four

Experimental Design

To perform this study, two test systems were required: a pressure measuring and data acquisition system and an aerosol test system. The same respirators has been used for both the pressure measurement and aerosol measurement tests. These respirators has been modified to control the leak location and leak hole size.

4.1 Pressure Measurement System

The pressure measurement system consisted of a pressure transducer and data acquisition system. The pressure transducer was mounted on a useful platform for attachment to the different respirators. A collapsable diaphragm was design to produce a negative pressure inside the sealed respirator. This system was used to produce, measure and save the pressure decay data for each test.

4.1.1 Pressure Transducer

Selection of the pressure transducer was based on three criteria: weight, response time and operational range. The pressure transducer was located on the respirator at the filter position. The weight of the pressure transducer could

cause a torque on the respirator which could affect the face/respirator seal. The weight limitation was found by wearing a respirator and placing known weights on one filter position. By observation, it was determined that a weight of greater than 50 grams produced a noticeable change in the face/respirator interface. The maximum weight of the pressure transducer was set at 50 grams.

The pressure decay rate for a given leak hole diameter, with the pressure transducer connected directly to the respirator cavity and no tubing in the test system was not known. Thus, there was no criteria for selecting the response time of the pressure transducer. A minimum response time of 50 msec for the pressure transducer was arbitrarily selected. The operational pressure range of the pressure transducer was set at 0.0 to 10.0 cm w.g.

With these criteria, several pressure transducers were evaluated from manufacture's literature. Most of the pressure transducers met the response time and operating range requirements but not the weight limitation. The pressure transducer selected (Model PX-160, Omega Engineering, Stamford, CT) was the only commerically available pressure transducer to meet all three criteria. The pressure transducer weight is 28 grams, has a response time of less than 10 msec and an operational range of 0.0 to 25 cm w.g. Calibration data are given in Appendix A.

4.1.2 Data Acquisition System

Once the pressure transducer was selected, a data acquisition system was needed. Conventional strip chart in the laboratory had maximum response times of 0.5 to 1.0 seconds. These were inadequate for the pressure transducer collection rate. Two options were available. First, a fast response time strip chart recorder could be procured. The second option would be the procurement of a computer based data acquisition system. The computer system was selected for future flexibility in the laboratory and for economics reasons.

The data acquisition system consisted of an analog to digital (A/D) converter (AC Jr., Strawberry Tree Inc., Sunnyvale, CA), a computer (Model 140, Heath Co., Benton Harbor, MI), and software (Unkelscope, Unkel Software Inc., Lexington, MA). The A/D converter was needed to change the pressure transducer analog signal into a computer recognizable digital signal. The A/D converter was selected strictly on cost. The computer used was selected based on immediate availability and was already present in the Industrial Hygiene Section. The software was selected for three reasons. The software obtained was completely menu driven, no programing was required. Also, the software had the ability to perform required data transformation on the collected data. Finally, this software was the least expensive.

4.1.3 Mounting of the Pressure Transducer

Initial studies indicated the use of any tubing affected the pressure decay rate. Thus, attachment of the pressure transducer to the respirator cavity could not include tubing. Metal fittings could not be used due to the weight limitations, Section 4.1.1. The mounting platform had to be lightweight and have a large cross sectional area as compared to the pressure transducer negative pressure port cross sectional area. After much consideration, a 37 mm filter cassette was selected. The cassette had a large cross sectional area, 3.7 cm, as compared to the pressure port, 0.5 cm, and was light weight. The cassette was made of a material which could be glued making construction easier.

A slight modification to the pressure transducer was made before mounting it on the cassette. The negative pressure port was reduced in length and expanded in diameter to reduce their slowing effects on air flow. The final shape of the negative pressure port was 0.5 cm in diameter and 0.1 cm in length. It should be noted, however, that the response time of the pressure transducer was reported by the manufacturer as less than 10 msec prior to the modification. The effects of the modification were not known.

The male half of the cassette was smoothed even on a lathe. After determining the location of the negative pressure port with respect to the cassette, a 0.64 cm hole was drilled. The pressure transducer was then glued to the

cassette. Figure 4.1 is a representation of the pressure transducer mounting. Connecting the mounted pressure transducer to the respirator cavity was accomplished by the use of a coupling described in Section 4.3.

4.1.4 Collapsable Diaphragm

To produce the negative pressure in the sealed respirator cavity, two options were considered. The first option required the subject to produce the negative pressure by inhaling a small amount of air after the respirator cavity was sealed. The second option required the experimenter to produce the negative pressure by some sort of mechanical device. The second option was selected. It was found to be difficult for the subject to remove the same amount of air each time. Also, while the subject was attempting to recover from the small inhalation, the facial movements were causing an erratic pressure signal. By allowing the experimenter to apply the negative pressure, a smooth decay curve was obtained.

To produce the negative pressure in the sealed respirator, the ideal gas law was applied. In a sealed space, an increase in volume will produce a corresponding decrease in the pressure. To do this, a collapsable diaphragm was attached to the respirator cavity which could be activated by the experimenter.

The design of the collapsable diaphragm was dictated by the design of the pressure transducer mounting. Both the collapsable diaphragm and pressure transducer had to be attachable to the respirator cavity by the same coupling. The collapsable diaphragm was constructed by placing a thin synthetic rubber membrane, balloon cut to size, over a cassette extension and held in place by a male cassette, Figure 4.1. To activate the collapsable diaphragm, a 60 cm^3 syringe was attached to the male cassette by tubing. The tubing was not connected to the respirator cavity and did not affect the pressure decay. To produce the negative pressure in the sealed respirator cavity, the collapsable diaphragm was attached to the respirator cavity by the coupling and the syringe piston was pulled. This caused a negative pressure on the membrane. The membrane collapsed and increased the respirator cavity volume and decreased the respirator cavity pressure.

4.2 Aerosol Test System

A major objective of this study was the comparison of the measured pressure decay for a given respirator, leak hole size and leak location to the aerosol leakage for the same conditions. To accomplish this, an aerosol test system was required. Available in the laboratory was an aerosol test system recently used (Holton, 1986) for respirator

penetration studies. For convenience, this system was used with minor modifications. The aerosol system included a detector, test chamber, aerosol generator and an air delivery and removal system. A representation of this system is presented in Figure 4.2.

4.2.1 Detector System

A near-forward-light-scattering photometer (Model FE 250A, Frontier Enterprises, Albuquerque, NM) was used to detect the aerosol. This particular device is part of a field level respirator fit testing system commonly used. Thus, it was an ideal piece of equipment to use for the comparison study.

The photometer measures the total light scattered from a cloud of particles and is dependent on the size distribution and composition of the aerosol (Hinds, 1981). The photometer reading is a relative index of particle concentration and is not an absolute measurement of the aerosol concentration. In this study, it is assumed that the particle distribution and composition are stable. This was tested to be correct. Concentration variation was less than five percent. The aerosol concentration in the chamber is arbitrarily set at 100. The photometer reading is saved on a strip chart recorder (Model 194, Honeywell-Electronik, Fort Washington, PA).

The photometer was located outside the test chamber. To sample the test chamber and respirator cavity, sampling lines were required to transport the test aerosol to the photometer. The two existing sampling lines located on the test chamber were utilized. One sampling line was connected to the respirator cavity while the inlet of the other sampling line was located in the test chamber near the subject's face. Both sampling lines were of the same length, 75 cm, and the same diameter, 0.64 cm. The paths of the sampling lines were the same. By using the same size sampling lines and paths, the effects of sampling line losses were diminished.

The sampling rate of the photometer was two liters per minute. The transport time of the aerosol to the photometer was 0.7 sec.

4.2.2 Test Chamber

The test chamber used in this study was constructed for a previous study (Holton, 1986). Since the test chamber was designed for aerosol penetration tests, no modifications were made to the test chamber.

The test chamber is illustrated in Figure 4.3 (Holton, 1986). The inside dimensions are 190 cm high, 137 cm wide and 91 cm deep. The aerosol, after dilution, entered the chamber at the top through a 10.2 cm diameter PVC pipe. A dispersion plate, an aluminum disk 20.3 cm diameter, was

located 5.4 cm directly beneath the aerosol entrance. The entering aerosol and dispersion plate were located in a plenum which has a height of 13 cm. The base of the plenum, ceiling of the test chamber, was perforated carbon steel. The holes were 1.59 mm in diameter and staggered 3.18 mm on center, giving a open area of 23%. To assist the dispersion plate in evenly dispersing the aerosol, four fans were located in the plenum's ceiling. A raised floor was constructed which allowed channeling of the aerosol out of the chamber. The plywood floor was supported by four wooden strips, 1.9 cm by 7.6 cm by 100 cm, evenly spaced to form the channels. Over each channel, 18 six mm holes were drilled. Air was removed from the test chamber through the floor and subfloor space by nine 2.5 cm diameter PVC tubes.

4.2.3 Aerosol Generation and Transport

To perform the aerosol leak test into a respirator cavity using a photometer as the aerosol detector, an aerosol must be generated. This aerosol must have a constant concentration and be detectable by the photometer. To generate this test aerosol, corn oil was nebulized and transported to the test chamber. Corn oil was chosen for its lack of toxic effects and it is generally used in aerosol respirator fit testing.

A one-hole Collison Nebulizer was used to generate the corn oil test aerosol. This generation system was chosen

based on availability and proven ability to generate a usable corn oil aerosol (Holton, 1986). The nebulizer was located at floor level for safety reasons. If the nebulizer would fall, there would be no danger to individuals in the laboratory. If the nebulizer leaked, the oil would not destroy papers, equipment and so forth.

Filtered house air at 9 psig was used in the aerosol generation system. The corn oil aerosol was directed through a roughing filter which removed particles with diameters greater than about 15 micrometers. From the filter, the aerosol was perpendicularly injected into a carrier air system. The carrier air was supplied by a pump (Model 0322-P102-G18, Gast Inc., Benton Harbor, MI) which pulled room air through an Ultra Air HEPA filter and then pushed the air into a 5.2 cm PVC pipe. The carrier air system was required to carry the aerosol from floor level to the top of the test chamber. Here the carrier air and dilution air merged at a "Y" fitting. The carrier air was transported in a 5.2 cm diameter PVC pipe at a rate of 0.3 m^3/min. The length of the aerosol path from injection into the carrier air to the test chamber was two meters. The transport time of the aerosol was 0.8 sec.

Dilution air was supplied by a fan (Size C, American Standard Industrial Products Division, Detroit, MI) located 2.7 meters above floor level. Due to the fan size and weight, the dilution air was piped to the "Y" fitting on top

of the test chamber rather than moving the fan to the chamber. The dilution air was forced through an MSA Ultra Air HEPA filter. The flow rate was 1.2 m^3/min. The flow rates of the carrier air and dilution air were determined from the desired residence time of the aerosol in the test chamber. If the dilution rate was to high, the aerosol would be too diluted for detection. Conversely, if the flow through rate was too slow, the time for the chamber aerosol to stabilize would be longer than desirable. A chamber residence time of between one to two minutes was arbitrarily selected. The test chamber volume was 2.37 m^3, the total air flow into the test chamber was 1.5 m^3/min, giving a chamber residence time of 1.5 min.

Infiltration of aerosol into the chamber was not desired. Infiltration might affect the the aerosol distribution and in turn affect the photometer response. However, by observation, the test chamber leaked into the room when using the passive exhaust system connected to the test chamber. To make the laboratory environment more tolerable and to aid in even flow inside the chamber, the existing exhaust system was modified. The nine pipes leading from the test chamber subfloor were connected to a 10.2 cm diameter PVC plenum. A fan pulled air through an MSA Ultra Air HEPA filter from this plenum. The exhaust air was released into the laboratory. A representation of the exhaust system is shown in Figure 4.4.

The test chamber was operated at a positive presssure of 0.32 cm w.g. This pressure was selected by default. With the supply air flow fixed and the exhaust fan running at maximum speed, the resultant pressure was 0.32 cm w.g. Since the system operated as desired, no other modifications were made.

4.3 Respirator Modifications

A goal of this study was to determine the effects of leak location and leak hole size on the pressure decay and measured aerosol leakage. To accomplish this, the experimenter needed to control for hole size and location. A representation of the modifications made to the respirators is shown in Figure 4.5. To compare pressure decay to aerosol leakage, it was desirable to use the same respirators for both test. To accomplish this, a coupling was constructed which allowed both tests to be performed on each respirator. Three respirators were used for this study, a MSA large, Surviveair medium, and a North medium. Each respirator was probed for sampling and artificial leak locations. Different size artificial leak holes were used to produce different fit factors. A coupling was constructed that allowed placement of the pressure transducer, collapsable diaphragm,

and filters on the respirator without the removal of the respirator from the subject's face. A representation of the coupling structure is shown in Figure 4.6.

4.3.1 Sampling Probe

To sample the respirator cavity during the aerosol test, the respirator required a sampling probe. Sampling probe selection was based on using the same size probes used in field respirator fit testing and a previuos aerosol penetration study on respirators (Holton, 1986). The respirator cavity was probed by a brass fitting, 0.5 cm I.D., length 3 cm. A viton o-ring was placed on the threaded end of the probe, inserted in a hole on the respirator and secured by a brass nut. The hole for the probe was located directly in front of the nose area. The probe depth into the respirator cavity was 0.5 cm.

4.3.2 Artificial Leak Locations

To simulate as best as possible true leaks in the face/respirator interface, the artificial leak locations were on the periphery of the respirator. There were three locations on each respirator, top at the bridge of the nose, center right above the filter on the subject's right side, and the bottom in front of the chin. At each leak location, a probe was inserted for attachment of the different leak holes. The probe size was a compromise between large enough

to work with during testing and small enough as not to effect the test results. The probes were made of 3 cm long, 0.4 cm I.D., copper tubing. A tygon perforated plug was placed on the inside end of the copper tube to keep the copper tubing from contacting the face and to direct the air flow parallel to the face surface. The probes were kept in place by a rubber gasket forced over the tubing and against the respirator outer surface.

4.3.3 Artificial Leak Holes

To obtain different leak rates into the respirator cavity, different diameter leak holes were used. The diameters chosen were based on a previous study (Holton, 1986). Four artificial leak holes were made from 0.50 cm diameter plexiglass rod. Each leak hole was 0.50 cm long. The leak hole diameters were 0.046, 0.053, 0.071 and 0.081 cm. The holes were made by drilling, with the appropriate drill bit diameter, through the center of each piece of plexiglass. Each artificial leak hole was inserted in a tygon tubing sleeve, 1.5 cm long. For testing, the tygon tubing sleeve, with leak hole attached, was forced over the end of the copper tube of the appropriate location. Three pieces of tygon tubing, 1.5 cm long, were plugged with silicon glue and were used as caps for the leak tubes during testing.

4.3.4 Coupling

To standardize testing, the same respirator was worn for both pressure and aerosol testing. Based on the pressure transducer mounting, Section 4.1.3, a design for the coupling was made. To make the couplings, a Surviveair filter conector was fitted to the three respirator inlet ports. Two Surviveair filters were cut such that only the bases remained. On each base, the female half of a 37 mm filter cassette was attached. Two survive Air filters were then modified by placing the male side of a 37 mm filter cassette to the bottom of each. Thus, the couplings could be placed on all the respirators and the filters, pressure transducer and collapsable diaphragm could be fitted to each respirator on either side and removed without displacing the respirator from the subject's face.

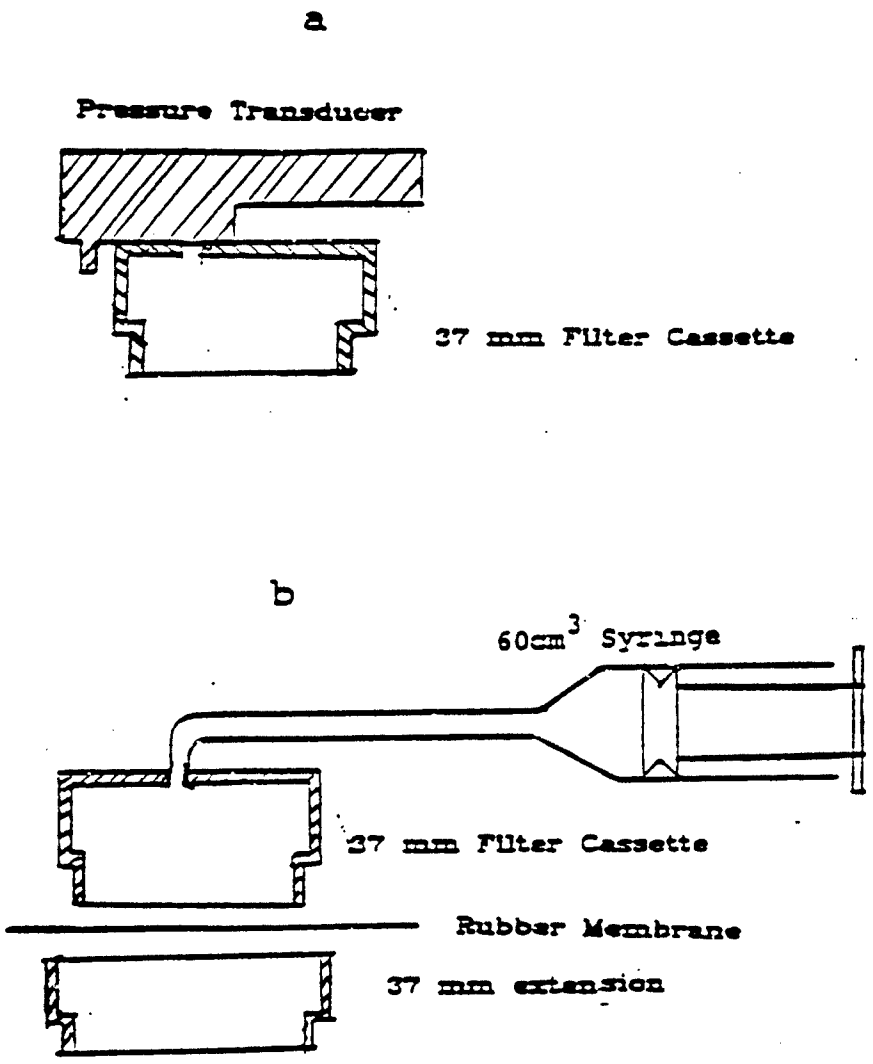

Figure 4.1 Equipment Used for Dynamic Pressure Test
a- Mounting of Pressure Transducer
b- Collapsable Diaphragm Used to Produce a Negative Presure in the Respirator Cavity.

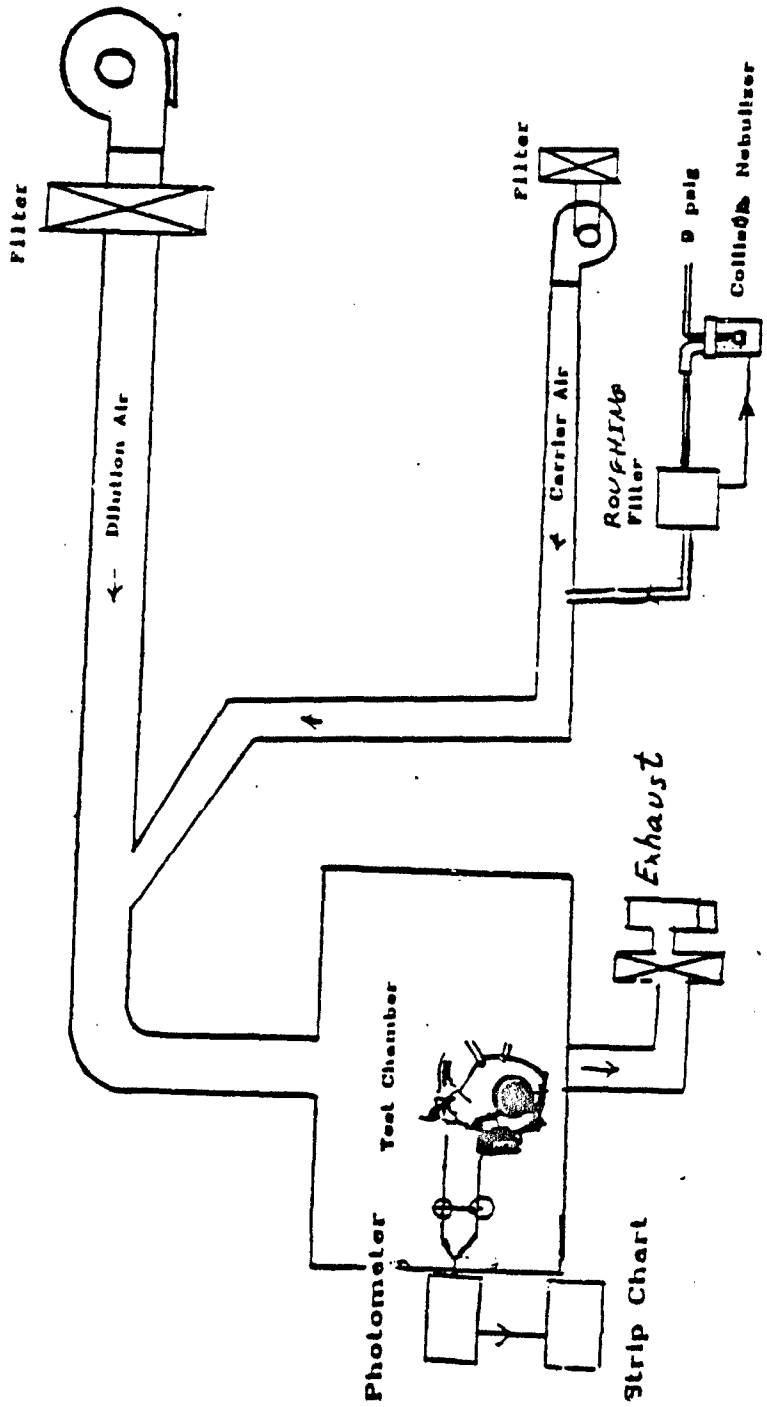

Figure 4.2 Aerosol Test System, This Diagram Represents the Generation, Transport and Detection of the Test Aerosol.

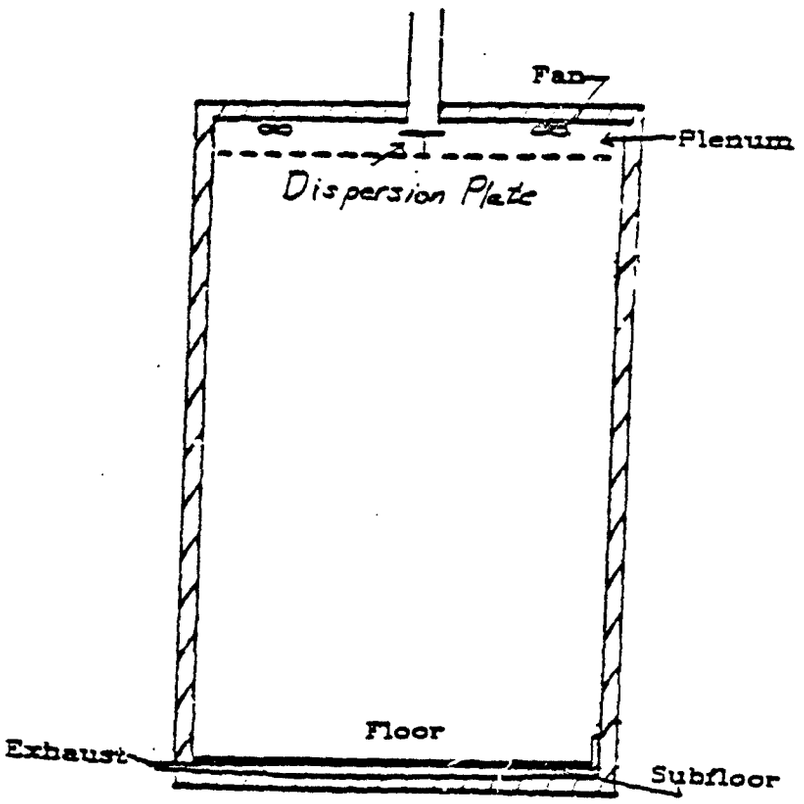

Figure 4.3 Test Chamber (Holton, 1986) Used for Aerosol Leakage Testing.

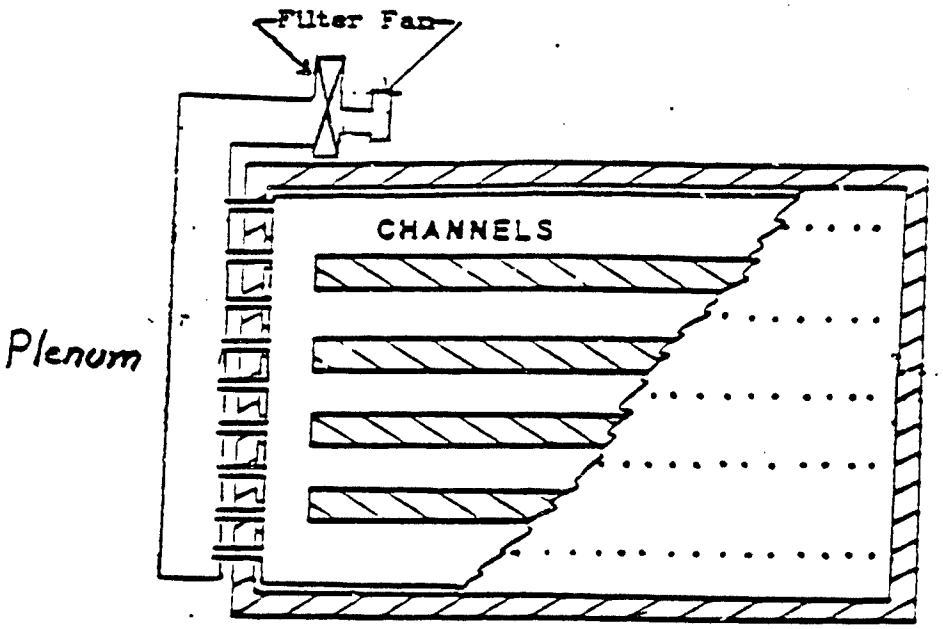

Figure 4.4 Exhaust System (adapted from Holton, 1986)

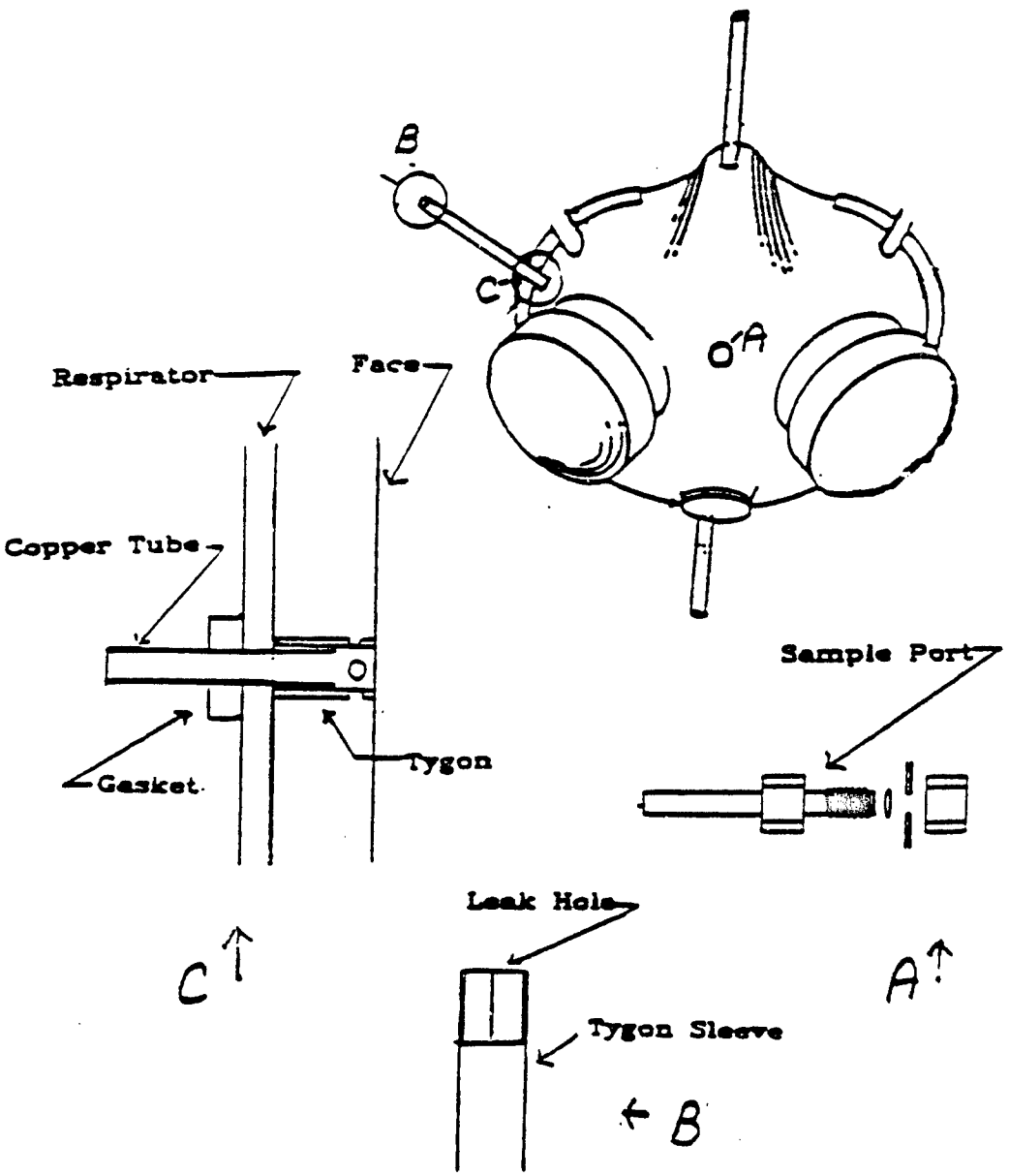

Figure 4.5 Respirator Modification,
a- Sample Probe,
b- Leak Hole Attachment to Respirator,
c- Insertion of Probe for Leak Location.

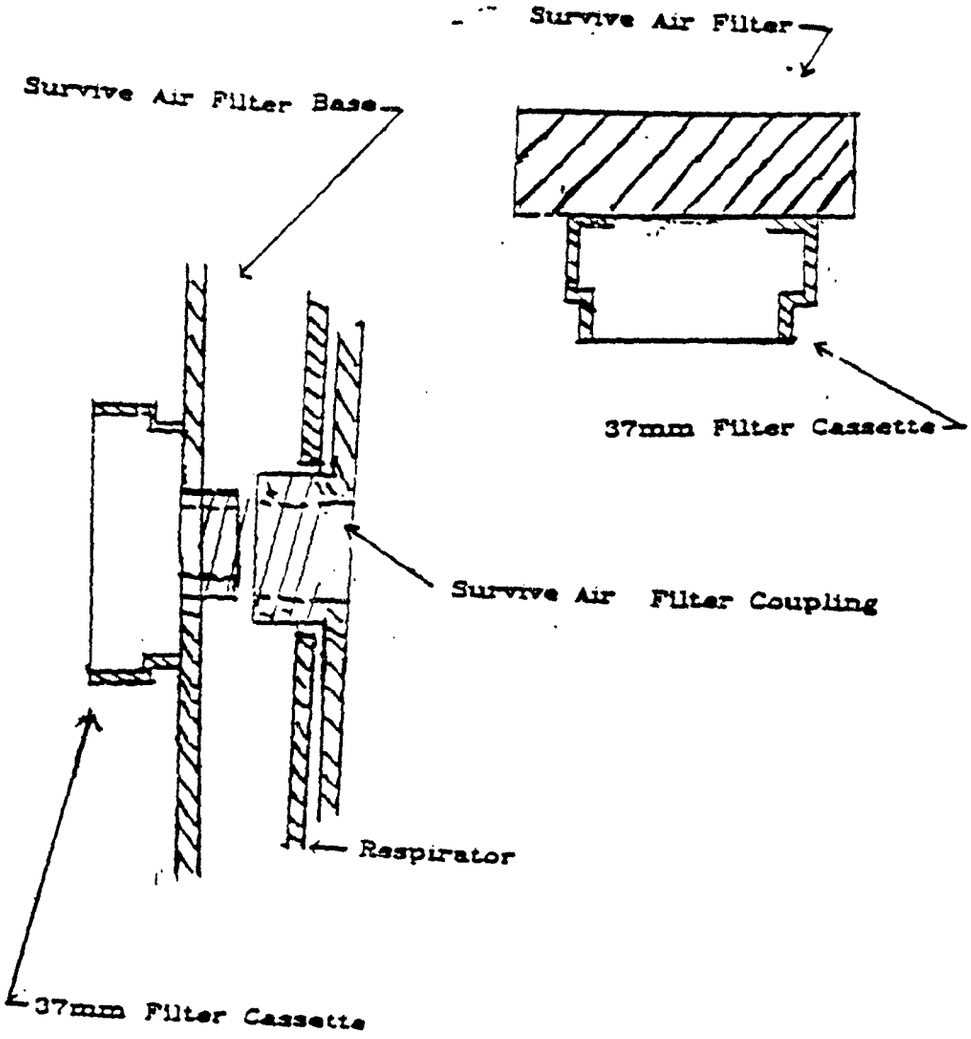

Figure 4.6 Coupling Used for the Attachment of Test Equipment to the Respirator.

Chapter Five

Procedure

The general test procedures consisted of several steps. The respirator was sealed to the subject's face and the face/respirator seal was evaluated to determine if any leakage was present. The proper equipment for either the pressure decay test or aerosol leakage test was mounted on the respirator coupling, and the testing was initiated. Figure 5.1 represents the testing scheme. To negate possible equipment effects, the test order was randomized for both leak location and leak hole diameter.

To determine the pressure change across the leak holes and filters for constant volumetric flow rates, a separate experiment was performed. This experiment was only preliminary in nature and further validation will be required.

5.1 Procedures Common to Both Tests

5.1.1 Sealing Respirator to Subject's Face

A combination of petroleum jelly, silicon weather sealant and Stomahesive Paste, a protective skin barrier cream used on stomas and fistulas, was used to seal the respirator to the subject's face. The petroleum jelly was

applied to the subject's face. It was found cleaning the face after the experiment was easier with the petroleum jelly used as a base coat. The Stomahesive Paste was applied to the respirator contact surface. The respirator was secured to the subject face and the silicon weather sealant applied at the face/respirator interface. This method obtained a sufficient seal in most attempts with no failure in the face/respirator seal during testing.

The seal was checked prior, during and after testing. To determine if the seal was adequate, all leak locations were capped off. In the pressure test, a negative pressure was applied. If a pressure decay of greater than 50 percent was observed in ten seconds, the seal was redone. If the pressure decay was less than 50 percent, the value was considered a baseline. In the aerosol test, after all locations were sealed off, the respirator cavity was sampled. If aerosol was detected at a concentration greater than 5 percent full scale deflection on the 0.1 range, the seal was redone. If the leakage was less than 5 percent full scale deflection on the 0.1 range, it was considered a baseline value. The baseline for each test was subtracted from all readings for that test.

5.1.2 Randomization of Order

To randomize the order of testing, all testing combinations were randomly drawn from a box. This included

each repeat measure. Thus, each testing location would be done twice with each of the four holes. Also, with the pressure test, the pressure transducer was located on both sides of the respirator giving two tests for each leak hole and location. There were a total of 48 samples per respirator for the pressure test and 24 samples per respirator for the aerosol test. The testing order is shown in Table 5.1.

5.2 Dynamic Pressure Test

The pressure decay test was performed in the laboratory. No special test environment was required. The respirator was sealed to the face and the seal checked. The testing began and followed the order listed in Table 5.1. The appropriate leak hole was attached to the appropriate location while the other locations were capped off. The pressure transducer was attached to one side of the respirator. The subject took a deep breath, the collapsable diaphragm attached to the other side of the respirator and activated. The pressure signal from the pressure transducer was sent to the A/D converter and then the computer. The pressure response was displayed on the computer monitor for observation and saved on disk. The test was run for ten seconds.

Table 5.1
Test Order

Test	Location	Hole
1	2	2
2	1	1
3	1	3
4	3	2
5	1	1
6	2	1
7	2	3
8	3	4
9	1	1
10	2	4
11	3	2
12	1	2
13	3	1
14	2	3
15	3	3
16	1	2
17	3	1
18	3	4
19	3	3
20	2	4
21	1	3
22	2	1
23	2	2
24	1	4

Location: 1=Top, 2=Middle, 3=Bottom
Hole: 1=0.046 cm dia, 2=0.053 cm dia,
3=0.071 cm dia, 4=0.081 cm dia

The software was configured to start collecting data at 8 cm w.g. as the negative pressure was increasing. Time zero corresponded to the 8 cm w.g. After the location was tested, the negative pressure pump and pressure transducer were reversed and the testing repeated. Thus, the pressure transducer was first on the subject's right side and then his left. This procedure was repeated for each test combination. Between the 12th and 13th test combination and after the 24th combination, the face/respirator seal was tested. This procedure was repeated for all three respirators.

5.3 Aerosol Test

After the respirator was sealed to the subject's face, the subject entered the test chamber. A baseline was performed to check the seal. In the order mentioned in Table 5.1, each test combination was sampled. The leak holes provided the fixed leak. To standardize the results of the tests, no head movements or exercising was performed. Breathing was at a resting rate. Between the 12 and 13th tests and after the 24th test, the face/respirator seal was retested to determine if any breakage of the seal occurred.

The ranges used on the photometer were 100, 10, 1.0 and 0.1 percent full scale. The 0.01 range was not stable during initial testing and was not used. The test chamber

concentration was set at 100 on the 100 range scale. The zero was set on the 0.1 range scale. It was determined, by observation, that 30 seconds were needed for the reading of the photometer to stabilize when sampling the respirator cavity. This stabilization time was not the result of the transport time of the aerosol to the photometer. Rather, it is believed to be a combination of equipment response time and time for equalization of the aerosol in the respirator cavity and the sampling line.

It should be noted that the concentration measured is not an absolute value. Rather, the concentration in the test chamber is arbitrarily set to 100 on the 100 range scale. All other readings are then a fraction of this arbitrary value.

5.4 Determination of Respirator Cavity Volume

To determine the respirator cavity volume from the leak slope method, a calibration graph is required. To produce this graph, the pressure decay must be known for specific respirator cavity volumes and leak hole diameters. In this study, the pressure decays were known from the calculations and the leak hole diameters were predetermined. To produce the calibration curves, the respirator cavity volumes had to be determined.

After all pressure and aerosol tests were performed, the respirator cavity volumes were determined by direct measurement with water. The exhalation valve was sealed closed by silicon weather sealant to prevent leakage of the water. The top leak probes were removed from each respirator, a funnel inserted in the hole and the respirator secured to the subject's face. A male 37 mm filter cassette replaced the pressure transducer fitting on the one coupling and the collapsable diaphragm was placed on the other coupling. The collapsable diaphragm was activated and water metered into the respirator cavity until the respirator cavity was full.

5.5 Determining Pressure Change Across Leak Holes and Filters for Fixed Volumetric Flow Rates

To determine the pressure change across the leak holes and filters at different volumetric flow rates, air was pulled through the leak holes and filters at a constant rate. The pressure was measured next to the orifice of study. The pressure was monitored by the pressure transducer used in the pressure decay test.

To produce the low flow rates, less than 100 cm^3/min, a syringe pump (Model 975, Harvard Apparatus, Millis MS) was used. To produce air flows greater than 100 cm^3/min, a vacuum pump (Model 115657, Ametak lab Electronics Division,

Kent OH) was used. To measure the flow rates under 4000 cm^3/min, bubble meters were attached to the orifice, after the pressure measurement was made. Flow rates over 4000 cm^3/min were measured by a direct reading rotometer.

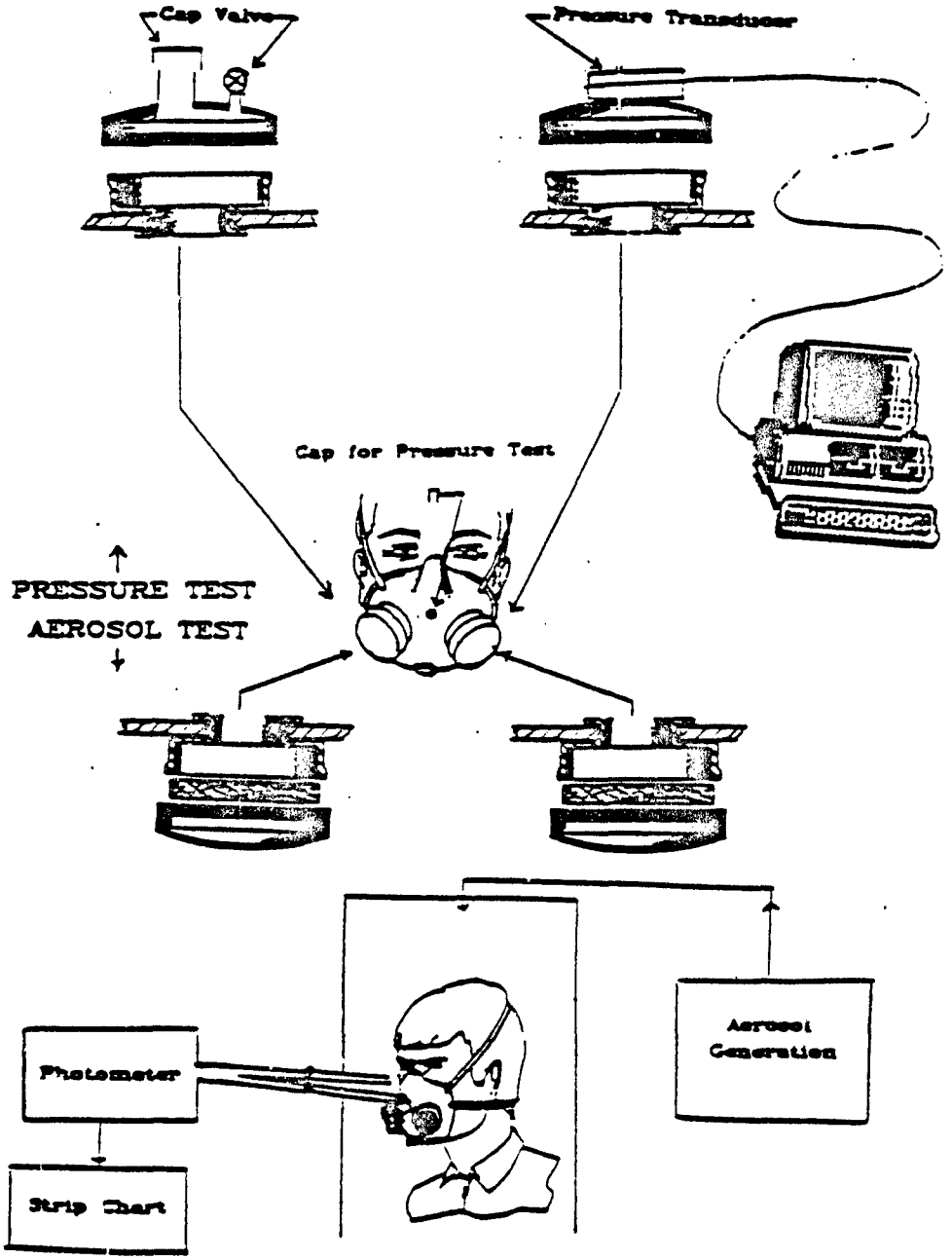

Figure 5.1 Schematic of Testing Procedure, The Test System Allowed Both Pressure Decay and Aerosol Leakage Measurement with the Same Respirator.

Chapter Six

Results

The pressure decay data were stored on disk for later interpretation. The aerosol leakage data were stored on strip chart paper. Since the aerosol data were reduced graphically, it was decided to reduce the pressure decay data in the same manner so not to bias comparisons made between pressure and aerosol data.

6.1 Aerosol Results

The data were from the graph paper. Readings were taken from the graph paper at 1.0 second time intervals. Each test was run for 20 seconds after signal stabilization. Thus, 20 values were used in determining the aerosol leakage. To determine the leakage, percent leakage and fit factor, equations 3.1, 3.2, 3.3 and 3.4 were used. Figure 6.1 shows a typical strip chart recording for this experiment. As seen in this figure, the aerosol concentration fluctuates during the test. This cyclic motion is due to several reasons. A possible explanation of this pattern is the periodic mixing of the aerosol by the user's breathing pattern. As the subject exhales, there is a great deal of turbulence in the respirator cavity, which leads to better mixing. When the

subject inhales, the air flows are streamlined into the nose and mouth area, reducing the amount of air at the sampling probe location. The pressure in the respirator cavity is changing as the subject breathes, this changes the amount of aerosol leakage and clean air in the respirator cavity. Also, there is deposition losses that reduces the exhalate. Table 6.3 lists the baseline test results. Table 6.4 list the aerosol test results corrected by baseline values.

6.2 Pressure Decay Result

The pressure decay data, on disk, was transformed by the computer to give the natural logarithm of the pressure data. Then both the linear and logarithm decays for the test were printed out. The resulting output was enlarged on a copy machine for graphical interpretation. The line of best fit, determined visually, was drawn with a straight edge. The slope of the decay curve, the leak slope, was determined from equation 3.5. The limits on the pressure decay were arbitrary and were set between 8.0 and 1.5 cm w.g. Figure 6.1 shows a typical computer printout and line of best fit for the pressure data. As seen in this figure, the leak slope is much easier to calculate than the aerosol leakage. The line of best fit is drawn and two points are used in the calculations. Table 6.3 lists baseline test results. Table 6.4 list the leak slopes corrected by the baseline values.

It should be noted that all tests were run for ten seconds, but the printouts were adjusted to give the best delineation of the decay curves. Table 6.1 gives the time required for the decay curve, 8 to 1.5 cm w.g.

6.3 Respirator Cavity Volume Results

The respirator cavity volumes are listed in Table 6.2. The measured volumes are a combination of the respirator cavity, the collapsable diaphragm and a male half of a 37 mm filter cassette. The error of the volume measurement was not determined by repeated measure. The procedure was quite uncomfortable to the subject and the error was estimated at 5 cm^3.

6.4 Pressure Change Across the Leak Holes and Filters for Different Volumetric Flow Rates

The measured flow rates through the filters and leak holes are listed in Table 6.5. The focus of this study was not on this issue. This data is preliminary in nature and requires additional study to determine repeatability.

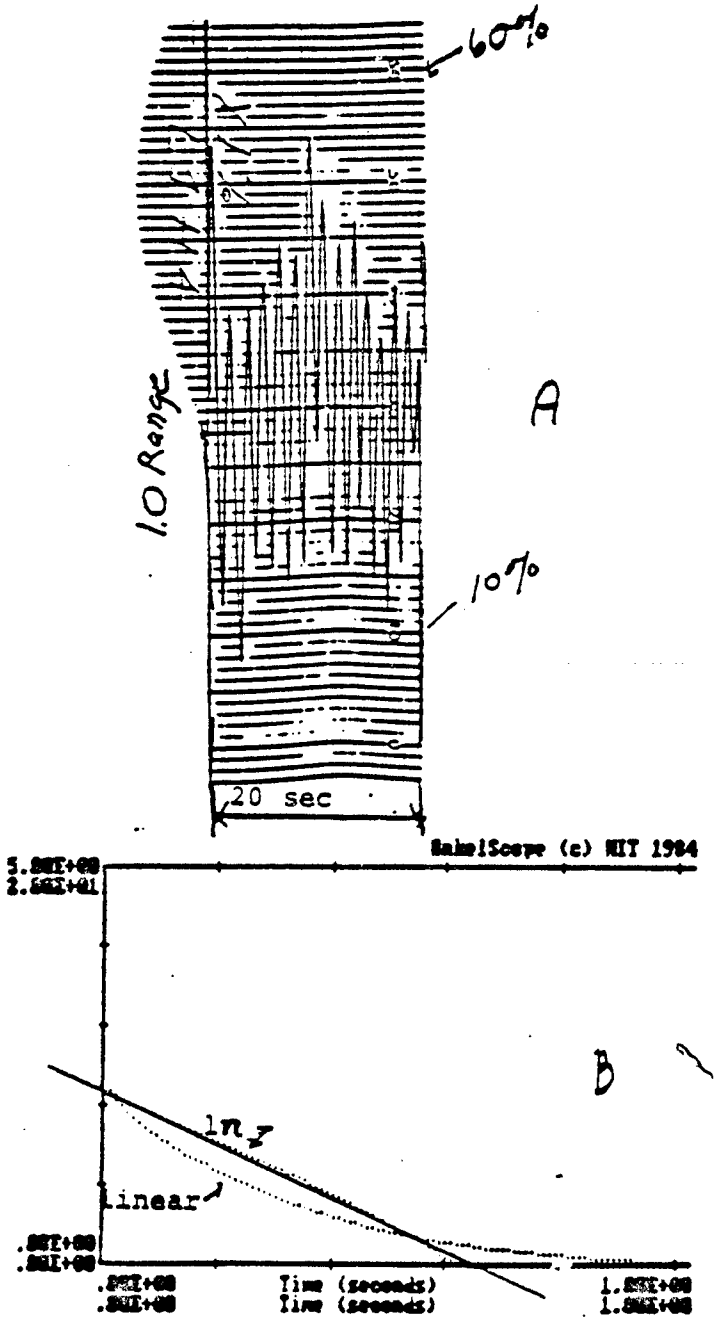

Figure 6.1: Typical Response Outputs
a: Aerosol Method Output: Range-1.0
Time of Sample- 20 sec.
b: Pressure Decay Method Output:
Linear Pressure Scale- 0-20 cm w.g.
Ln Response Scale- 0-5.(no units)

Table 6.1

Time for Pressure Decay, 8 to 1.5 cm w.g.

Hole Dia (cm)	Time (sec)
0.046	10
0.053	5
0.071	2
0.081	1

Table 6-2

Volume of Respirator Cavity, Collapsable Diaphragm Pump and Male Half of 37 mm Filter Cassette

Respirator	Brand	Volume (cm^3)
A	Surviveair	190
B	MSA-large	220
C	North-medium	170

Table 6.3

Baseline Data

Test	Mask	Leak Slope (1/sec)	Aerosol Leakage Range- 0.1 Scale
Pre	MSA	0.046	0.0
Middle	MSA	0.036	0.0
Post	MSA	0.042	0.0
Pre	S.A.	0.035	2.0
Middle	S.A.	0.037	3.0
post	S.A.	0.043	1.0
Pre	North	0.026	0.0
Middle	North	0.031	0.0
Post	North	0.035	0.0

S.A.- Surviveair

Table 6.4

Complete Data List, with all Values are Corrected for Baseline

		Survive Air, medium			MSA, large			North, medium		
Loc	Hole	Side 1 l/sec	Side 2 l/sec	Aero fraction	Side 1 l/sec	Side 2 l/sec	Aero fraction	Side 1 l/sec	Side 2 l/sec	Aero fraction
1	1	0.183	0.159	0.00006	0.114	0.069	0.00035	0.214	0.211	0.00044
1	1	0.173	0.189	0.00008	0.095	0.045	0.00029	0.214	0.197	0.00062
2	1	0.151	0.148	0.00006	0.051	0.089	0.00049	0.209	0.198	0.00090
2	1	0.183	0.193	0.00009	0.073	0.064	0.00031	0.192	0.237	0.00110
3	1	0.295	0.257	0.00020	0.092	0.058	0.00019	0.219	0.233	0.00114
3	1	0.195	0.233	0.00027	0.089	0.070	0.00034	0.186	0.212	0.00095
1	2	0.557	0.614	0.00065	0.406	0.445	0.00082	0.649	0.620	0.00091
1	2	0.576	0.578	0.00079	0.407	0.508	0.00106	0.623	0.817	0.00108
2	2	0.578	0.556	0.00068	0.466	0.439	0.00074	0.649	0.656	0.00106
2	2	0.638	0.606	0.00083	0.483	0.384	0.00103	0.641	0.754	0.00129
3	2	0.608	0.62?	0.00138	0.358	0.483	0.00129	0.619	0.678	0.00143
3	2	0.612	0.628	0.00167	0.398	0.496	0.00178	0.619	0.674	0.00133
1	3	1.405	1.486	0.00152	1.100	1.070	0.00192	1.631	1.716	0.00176
1	3	1.551	1.515	0.00198	1.020	1.027	0.00194	1.593	1.642	0.00210
2	3	1.360	1.668	0.00221	1.085	1.195	0.00184	1.680	1.742	0.00193
2	3	1.529	1.491	0.00289	1.061	0.984	0.00160	1.716	1.820	0.00222
3	3	1.595	1.573	0.00474	1.265	0.945	0.00253	1.690	1.768	0.00341
3	3	1.616	1.644	0.00617	1.133	0.945	0.00216	1.768	1.656	0.00353
1	4	2.969	2.928	0.00397	2.008	2.070	0.00312	3.374	3.370	0.00367
1	4	3.018	3.051	0.00529	1.883	1.945	0.00323	3.330	3.551	0.00264
2	4	3.058	3.037	0.00413	1.945	2.008	0.00319	3.179	3.276	0.00340
2	4	3.145	3.028	0.00549	1.820	1.999	0.00357	3.548	3.362	0.00326
3	4	2.961	2.961	0.00952	1.976	2.120	0.0694	3.251	3.409	0.00641
3	4	3.058	2.596	0.01266	1.851	1.695	0.00476	3.256	3.509	0.00505

Loc: Leak location:1-Top, 2-Center Right, 3-Bottom
Hole: Hole Diameter: 1-0.046 cm, 2-0.053 cm, 3-0.071 cm, 4-0.081 cm
Side: Location of Pressure Transducer: 1-Right Side, 2- Left Side
Aero: Aerosol leakage

Table 6.5

Pressure Change Across Leak Holes and Filters
for Fixed Volumetric Flow Rates

Flow Rate	Pressure, cm w.g.					
	Hole Diameter, cm					
cm^3/min	0.041	0.053	0.071	0.081	F1	F2
6.17	0.117	0.079	-	-	-	-
8.17	0.171	0.112	0.025	-	-	-
12.00	0.274	0.171	0.052	0.020	-	-
16.98	0.366	0.247	0.074	0.025	-	-
23.69	0.604	0.360	0.095	0.041	-	-
33.31	0.807	0.550	0.144	0.052	-	-
46.46	1.414	0.820	0.204	0.074	-	-
154.63	8.937	5.900	1.091	0.382	-	-
310.54	-	20.137	3.688	1.416	-	-
481.50	-	-	7.692	2.769	-	-
643.98	-	-	13.266	4.716	-	-
811.80	-	-	-	7.151	-	-
1000	-	-	-	-	0.063	0.063
4000	-	-	-	-	0.214	0.171
8000	-	-	-	-	0.387	0.306
12000	-	-	-	-	0.550	0.441
16000	-	-	-	-	0.766	0.604
20000	-	-	-	-	0.982	0.766
24000	-	-	-	-	1.199	0.875
28000	-	-	-	-	1.416	1.037

F: Filter

Chapter Seven

Discussion of Results

For convenience and clarity, several figures will be presented using the leak hole diameter as a common reference for the leak slope and aerosol leakage comparisons. The major focus of this discussion will be on the effects of leak hole location and respirator cavity volume on the leak slope and measured aerosol leakage.

7.1 Effects of Volumetric Flow Rates on Pressure Differential Across Leak Holes and Filter

The volumetric flow rates through and corresponding pressure differentials across the leak holes and filters were measured. Figure 7.1 illustrates the trends observed. The flow through the filters are directly proportional to the pressure change across the the filters. This would indicate the b term in equation 3.10 is constant. However, for the leak holes there is an apparent nonlinear relationship in the operating pressure range of the respirators. This indicates the flow pattern through the leak holes are in a transition phase between laminar and turbulent flow. The relationship described in equation 3.10 is made complex by this nonlinear relationship of volumetric

flow to pressure change across the leak holes. As previously stated, evaluation of equations 3.6 through 3.9 would not be accomplished if a complex relationship developed. The remaining discussion will only deal with the effects of leak location and respirator cavity volume on the leak slope and measured aerosol leakage.

7.2 Effects of Leak Location and Respirator Cavity Volume on Measured Leak Slope and Aerosol Leakage

A scatter diagram of the collected data, Figure 7.2, indicates trends in the data. Low leak slopes correspond to low aerosol leakage rates. Conversely, large leak slopes correspond to large aerosol leakage rates. There is a greater scattering of the data at low leak slopes and aerosol leakage rates. To further explore these relationships, the data will be reviewed in terms of respirator cavity volume and leak location.

7.2.1 Effects of Pressure Transducer Location

The pressure transducer was connected to the respirator cavity at two different positions. The average leak slopes for both positions were equal. The pressure transducer position on the respirator cavity did not affect the measured leak slope. Since no effect was observed by

pressure transducer position, locations center right and center left were combined into center right for further analysis.

7.2.2 Effects of Leak Location

The respirators were tested at three locations, top, center right and bottom. The leak slope was not affected by the leak location while the measured aerosol leakage was. This is illustrated in Figure 7.3. In this figure, the leak slope for the different leak locations for the same leak hole diameters produces the same line each time while the aerosol leakage produces at least two lines. The locations top and center right, both above the filter inlet and mouth area, are roughly the same, while the bottom leak location, located beneath the filter inlets and mouth area, indicates a larger amount of aerosol leakage measured.

7.2.3 Effects of Volume

Three respirators of different cavity volumes were used. The leak slope was dependent on the respirator cavity volume. The aerosol leakage was not dependent on respirator cavity volume. This is illustrated in Figure 7.4. The larger the respirator cavity, the smaller the leak slope for constant leak hole diameter. To further explore this relationship, the data were rearranged. Figure 7.5 indicates the relationship between the leak slope and respirator

cavity volume for different leak hole diameters. As this figure indicates, the different leak hole diameters produce parallel lines. Since these lines are parallel, eventually the leak slope can be normalized to a standard volume. Also, by the use of a figure such as Figure 7.5, the respirator cavity volume can be determined by the pressure decay method by introducing a known leak hole diameter into the respirator cavity.

7.3 Confidence Intervals of Aerosol Leakage and Leak Slope for Fixed Leak Hole Diameters

In the aerosol test, the leak location affects the measured aerosol leakage. In a field level aerosol respirator fit test, the leak location is not known and the results can not be corrected for the leak location effect. Since no correction can be made to the measured aerosol leakage, it may be concluded the aerosol method should have a large expected error. In the pressure decay method, leak location does not have an effect on the measured leak slope. The respirator cavity volume affects the leak slope in a predictable and thus adjustable manner. Since the pressure decay method can be adjusted for known effects, it may be concluded the pressure decay method has a smaller relative error compared to the aerosol method. Figure 7.6 illustrates the 95 percent confidence levels achieved in this study. The

leak slope was not corrected for respirator cavity volume effects and the aerosol method was not corrected for leak location. It can be observed from Figure 7.6, that both methods have a greater relative error for the smaller leak hole diameter. However, the percent error of the pressure decay method is less than the percent error of the aerosol method.

7.4 Statistical Comparison of Leak Slope and Aerosol Methods

This study explored through limited testing the pressure decay method. Any broad generalizations of the results based on the limited number of subjects, one, respirators studied, three, and different leak holes used, four, could lead to erroneous conclusions. With this qualifying statement, an analysis of variance, ANOVA,-one way layout-fixed effects (Hayes, 1973, Buhyoff, 1983) was performed. This is not the most appropriate test for this data. A multivariate analysis would provide a more exact statistical analysis (Stevens, 1986) but was not avaible at the time of analysis. However, the statistical analysis of the data confirms trends observed in the graphical analysis. This was accomplished with the tests selected. Table 7.1 lists the correlations performed with the associated F-values, degrees of freedom and p-values. A p-value of one indicates a perfect correlation while a p-value of zero

indicates no correlation. In practice neither is achievable. To determine at which p-value to consider the effects significant, the following logic was used. An overall type one error, alpha error, of 0.05 was selected. Two dependent variables existed, leak slope and measured aerosol leakage. To achieve an overall alpha of 0.05 with two dependent variables, a p-value of 0.025 or less was considered significant (Stevens, 1986).

By using a p-value of 0.025 to determine which effects were significant, the statistical analysis supported the graphical interpretation. Both the leak slope and measured aerosol leakage were dependent on leak hole diameter. The leak slope is independent of leak hole location and pressure transducer location. The measured aerosol leakage is dependent on leak location. The leak slope is dependent on respirator cavity volume while the measured aerosol leakage is not.

7.5 Comparison of Leak Slope to the Fit Factor

The fit factor is the usual method of communicating the quality of the respirator face seal. The fit factor is frequently measured by determining the amount of aerosol leakage into the respirator cavity. It has been shown in this study and others that the leak location affects the measured aerosol leakage and in turn affects the reported

fit factor. It has been shown in this study that the pressure decay is not affected by leak location and the pressure decay method has a smaller relative error in measuring the same leak hole diameters. To determine if either testing procedure is more sensitive, a correlation between the fit factor and leak slope was made. Figure 7.7 illustrates the relationship. There is a very large 95 percent confidence interval. The slope of the line of best fit is appropriately one indicating the sensitivity of both tests are the same.

Table 7.1

Results of the Statistical Analysis, ANOVA

Test	F-value	d.f.	p-value
	Leak Slope		
location	0.01378	2,141	0.98710
volume	4.21764	1,142	0.01630
hole dia	555.828	3,140	<0.00001
side	0.00003	1,142	0.9 215
	Aerosol Leakage		
location	1.80645	2,69	0.17000
volume	0.77720	3,68	0.53230
hole dia	73.9514	3,68	<0.00001

d.f.- degrees of freedom

side- pressure transducer location

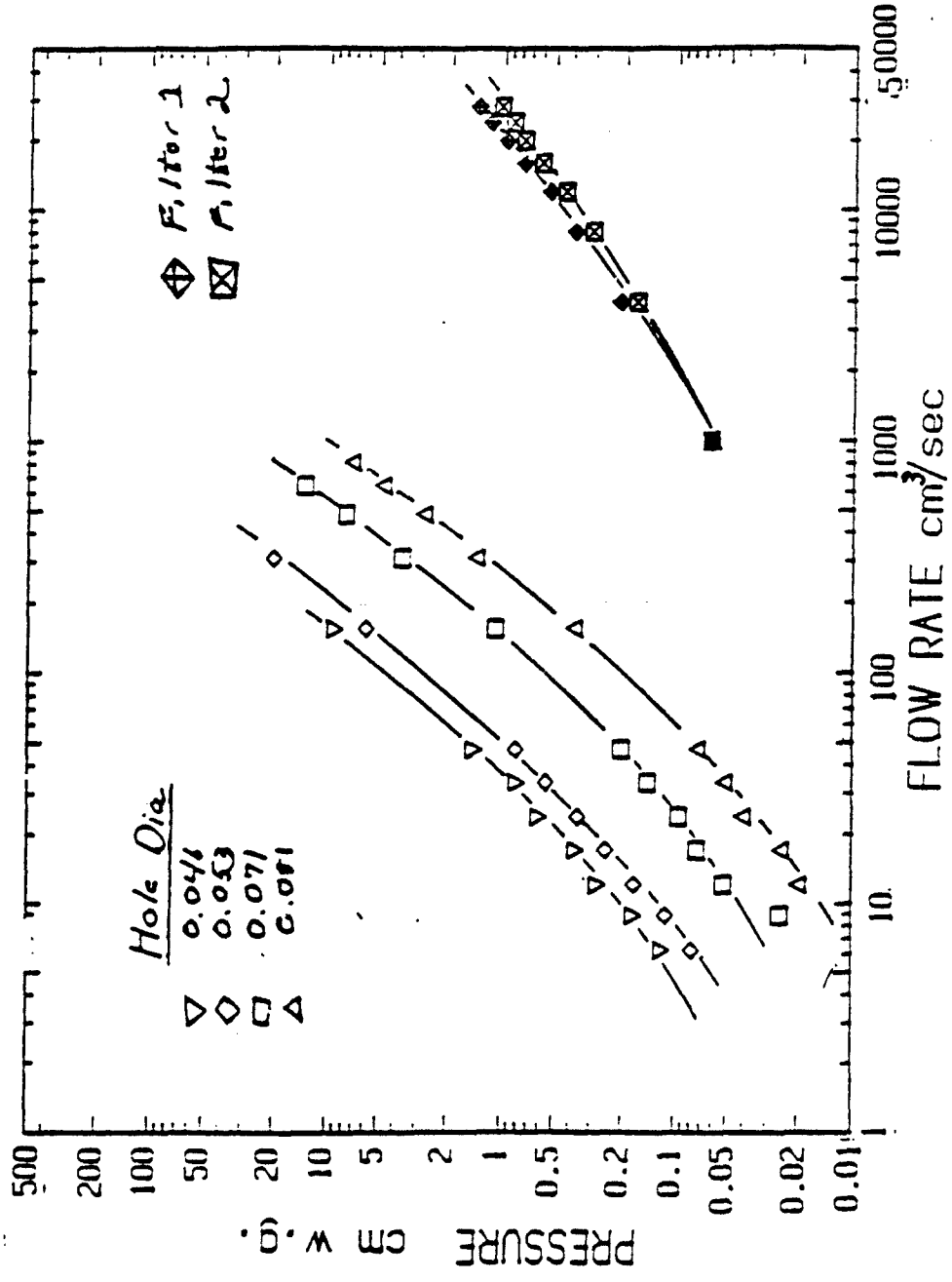

Figure 7.1 Effect of Hole Diameter on Volumetric Flow Rate and Pressure Change Across the Leak Hole.

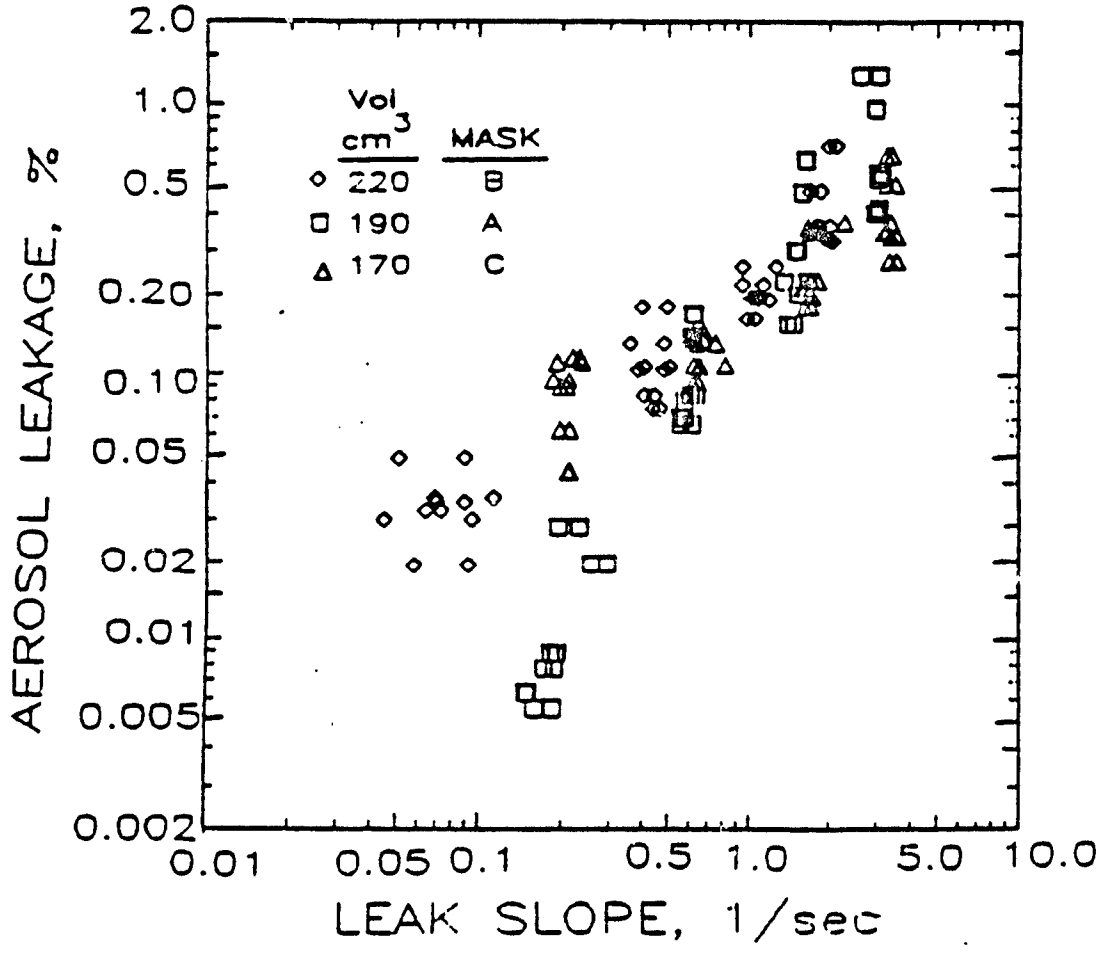

Figure 7.2 Scatter Diagram of All Data Collected.

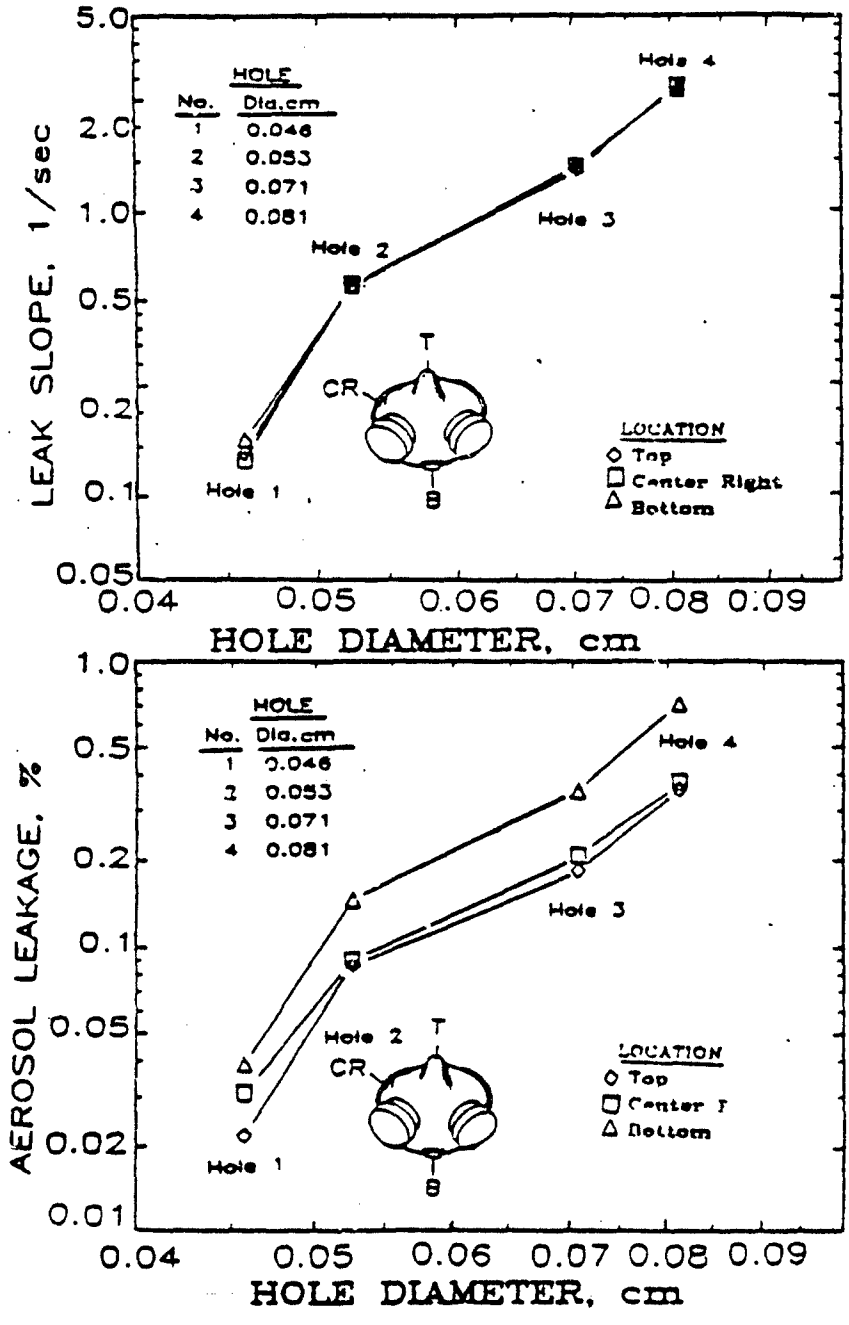

Figure 7.3 Effect of Leak Location on the Measured Leak Slope and Aerosol Leakage.

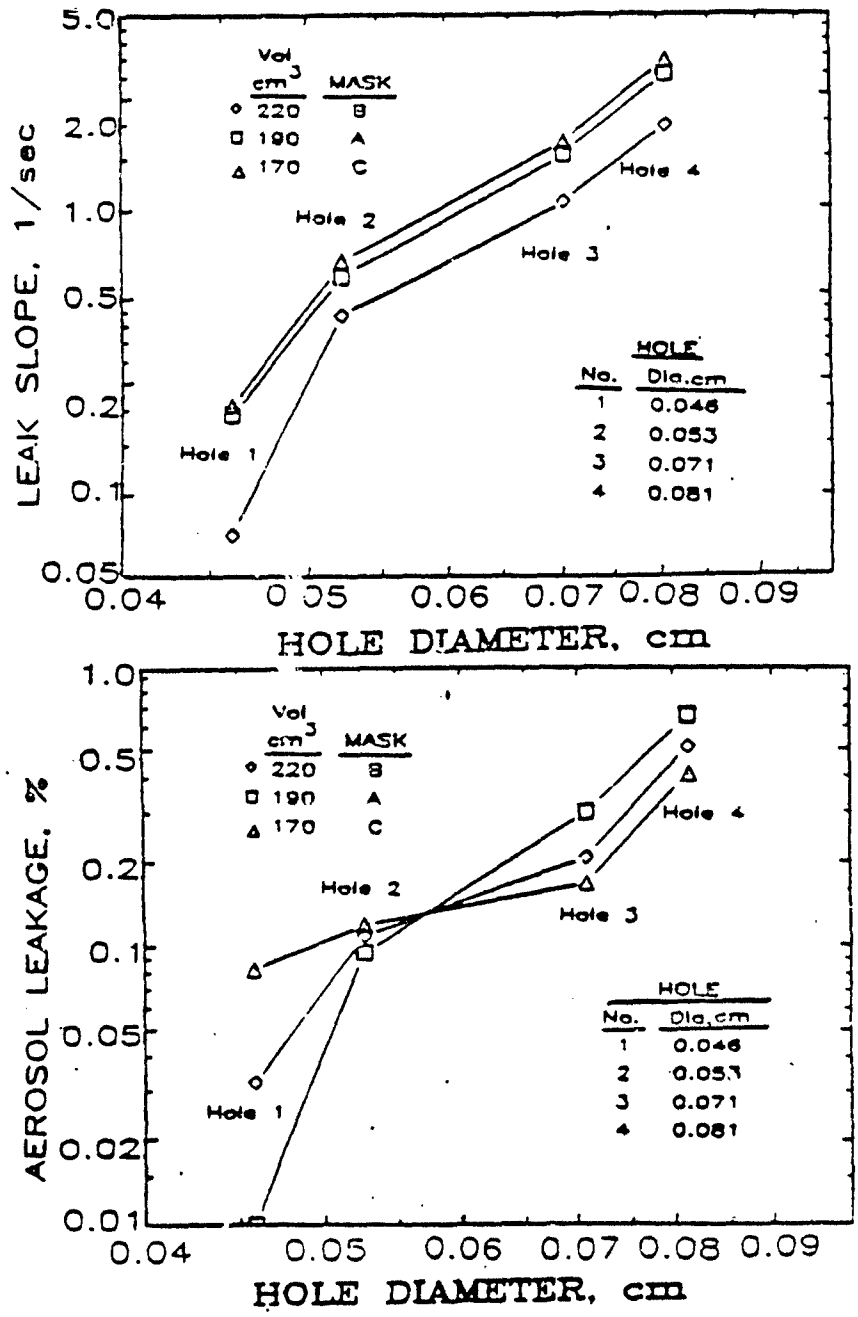

Figure 7.4 Effect of Respirator Cavity Volume on the Measured Leak Slope and Aerosol Leakage.

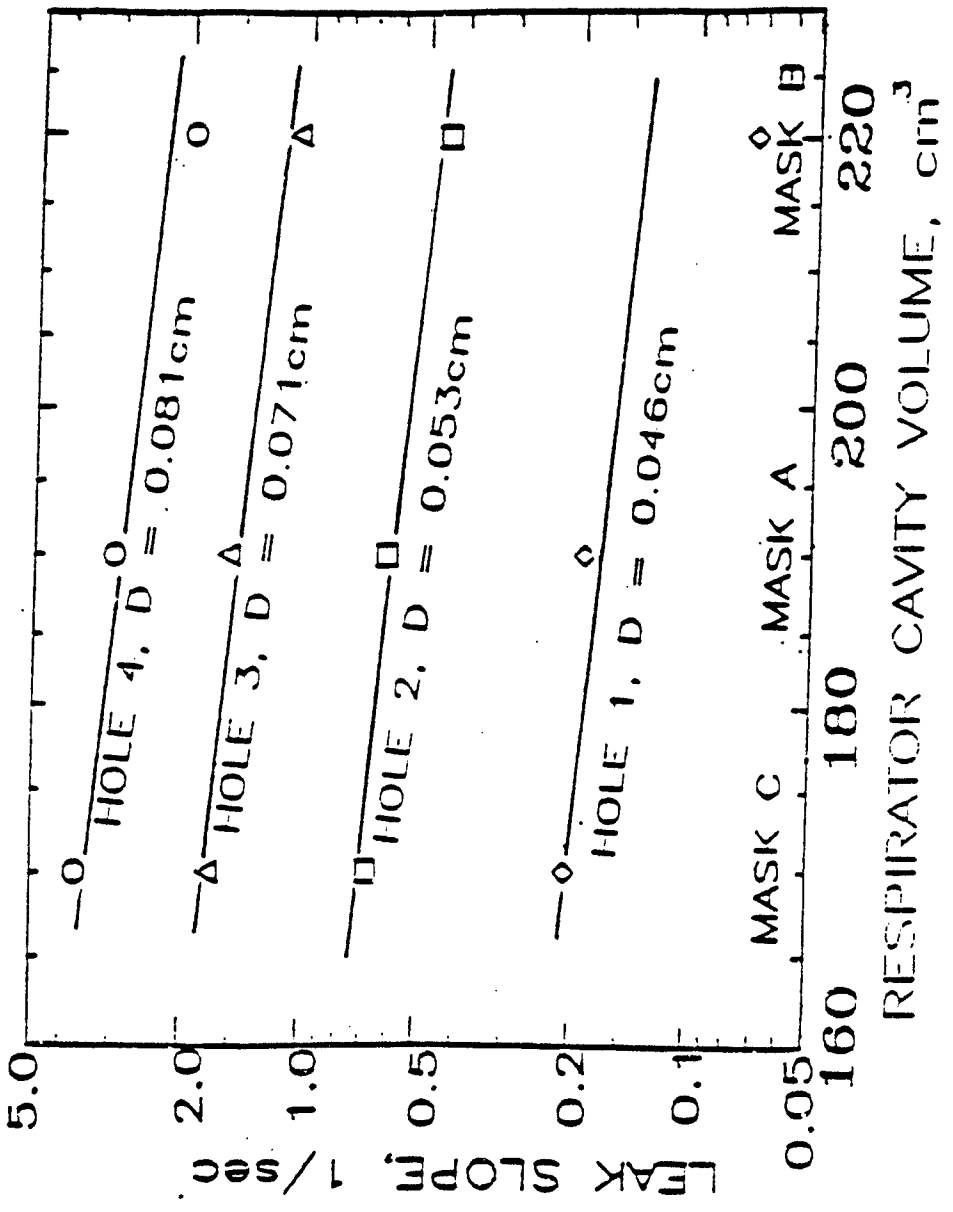

Figure 7.5 Relationship of Volume and Leak Slope for Constant Hole Diameter.

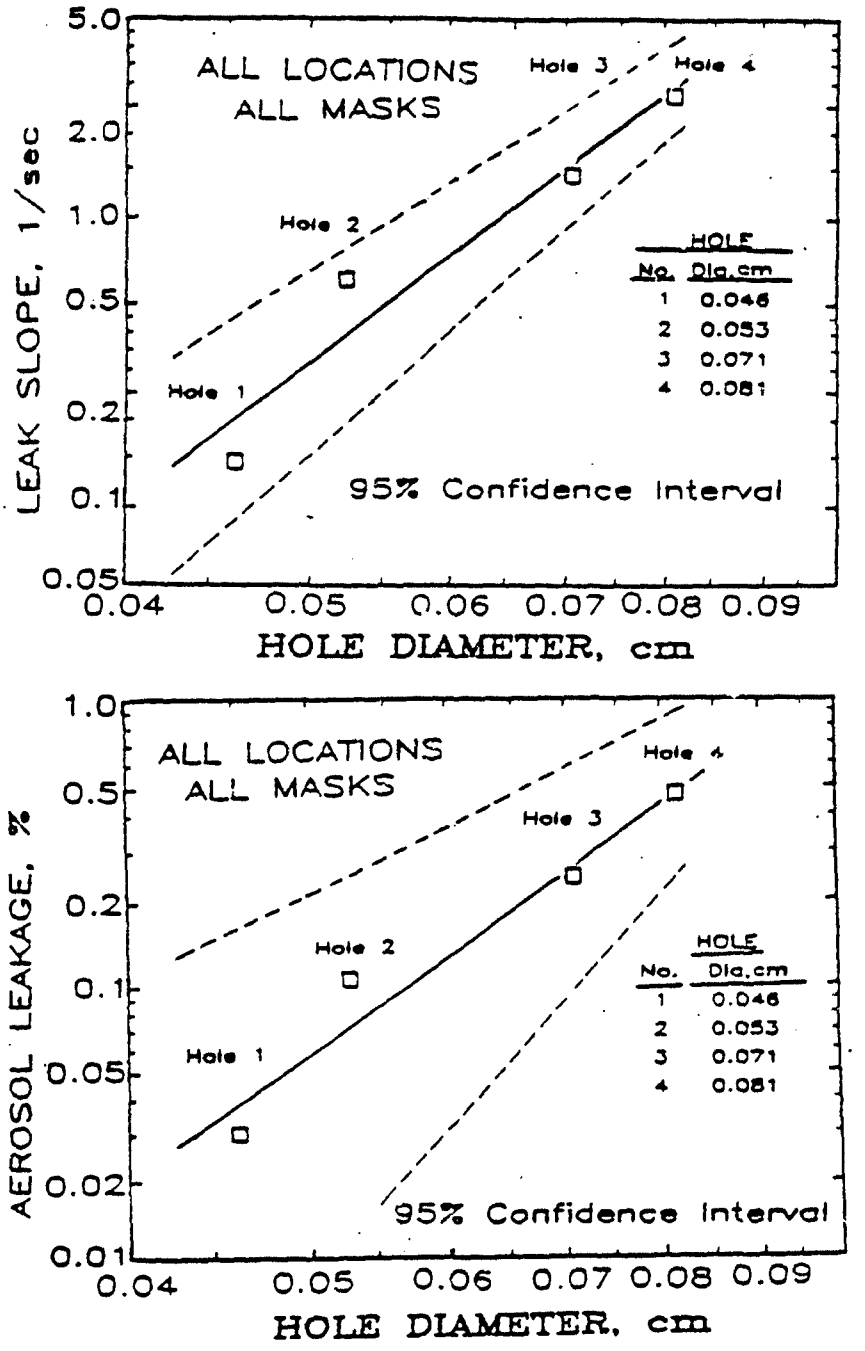

Figure 7.6 95% Confidence Interval for the Leak Slope and Aerosol Leakage Measurements for this Study.

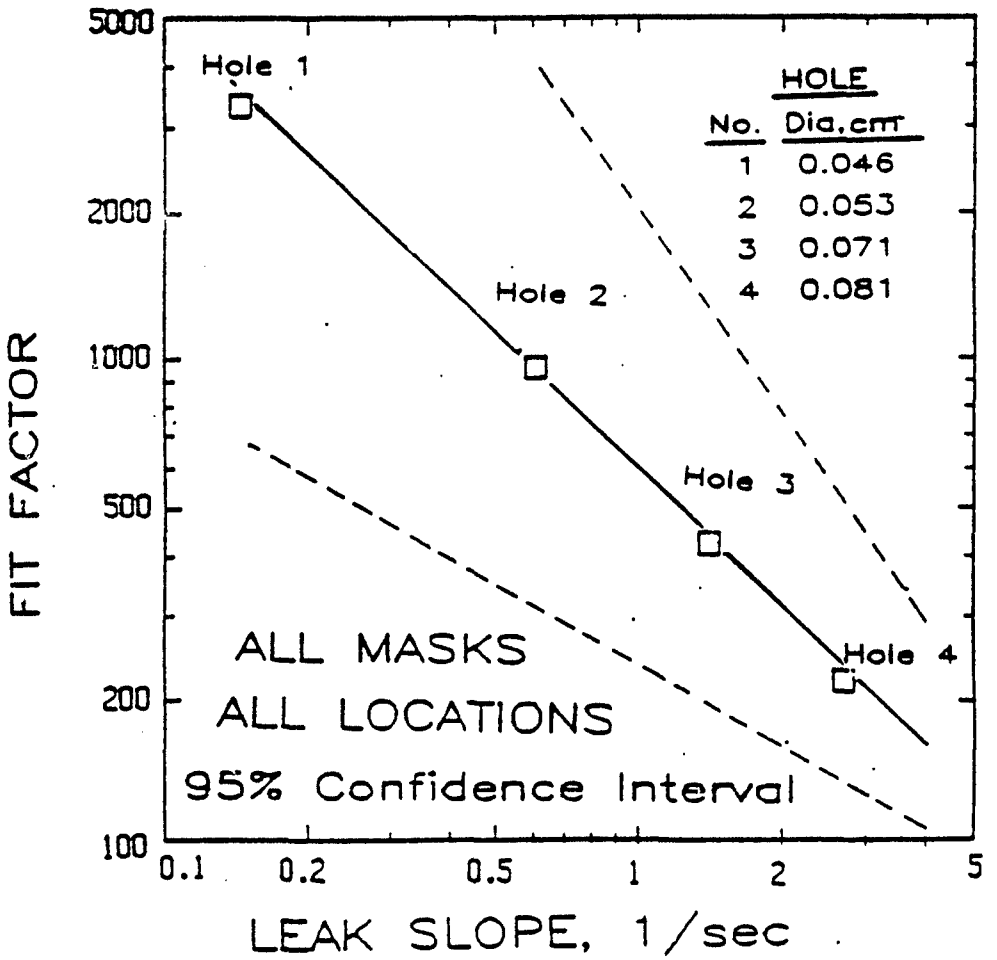

Figure 7.7 Comparison of Leak Slope to Fit Factor for the Same Hole Diameter and Location. Uncorrected for Leak Location and Respirator Cavity Volume.

Chapter Eight

Conclusions

The goal of this thesis was to perform initial testing on a new method of quantitative fit testing of respirators. The study address the issue of pressure decay in a sealed respirator. The leak slope was determined for different diameter leak holes in different locations. Also studied was the effect of volume on the measured leak slope and whether or not volume can be determined by this method. Then, the new method was compared to a traditional method of respirator fit testing. All goals of the thesis were achieved.

The pressure decay method of quantitative fit testing is independent of sensor and leak location. This method is dependent on the respirator cavity volume in a predictable manner. From this predictable effect, the respirator cavity volume can be determined from the leak slope and known leak hole diameter.

The pressure decay method has a smaller relative error than the traditional aerosol method and has the same sensitivity. The initial findings indicate the pressure decay method is a better test than the aerosol method for determining respirator fit factors.

All methods currently in use and the proposed pressure decay method rely on a short testing period. None of the methods truly measures the effects of changing work rates or respirator cavity pressures. Future studies should be in this area.

To understand the leakage into a respirator cavity, the mechanisms of fluid flow at low pressure through small holes needs to be understood. Preliminary data, requiring more study before definitive conclusions can be made, indicate the flow relationship to respirator cavity pressure is different for small holes and filters. As respirator cavity pressure is increased, the flow through the filters and leak holes increase. However, the increased flow through the leak holes is proportionally less than that of the filters. This indicates the fit factor is a function of leak hole size, respirator cavity volume, and work rate.

The best determination of fit factor needs to take into account these parameters. The present technology will allow determination of small flow rates at low pressure through small holes. By determining experimentally these values, a greater understanding of respirator leakage will be gained and a better estimate of worker protection can be made.

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Appendix One

Calibration of Model PX-160 Pressure Transducer, Omega Engineering, Stamford Conn.

The pressure transducer was calibrated by the use of an incline manometer, +/- 0.1 cm w.g. The results are listed in Table A1.1. Figure A1.1 is the gragh of the calibration data. The line of best fit, by the use of linear regression, was:

Pressure (cm w.g.) = 6.0416 x voltage - 5.6261

The r-value was 0.9994 with a Standard Estimate of the Error equal to 0.1146.

Calibration Data

Model PX-160, Omega Engineering, Pressure Transducer

Pressure, cm w.g.	Voltage, from transducer
0.0	0.905
1.0	1.084
2.0	1.268
3.0	1.449
4.0	1.620
5.0	1.782
6.0	1.929
7.0	2.08
8.0	2.23
9.0	2.41
10.0	2.59

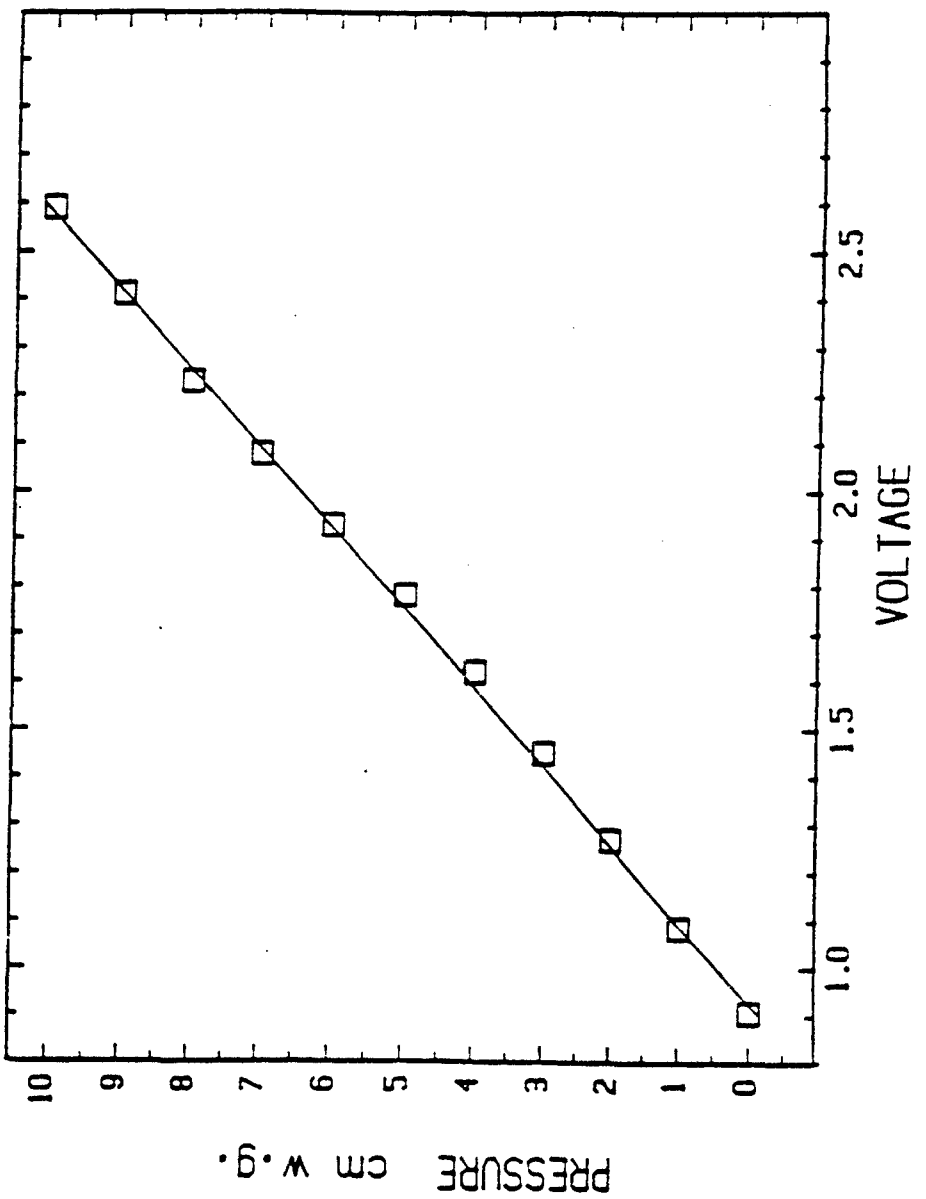

Figure A1.1 Calibration of Pressure Transducer, Model PX-160, Omega Engineering, Stamford Ct.